

CHEMICAL ENGINEERING

August
2019

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Industrial Gas
Purification

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Fingertips:
Heat Transfer

Controlling Dust

Focus on Pipes,
Tubes and Fittings

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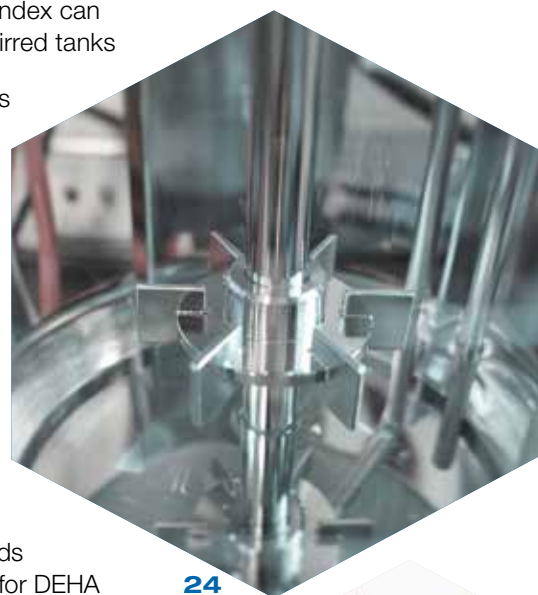
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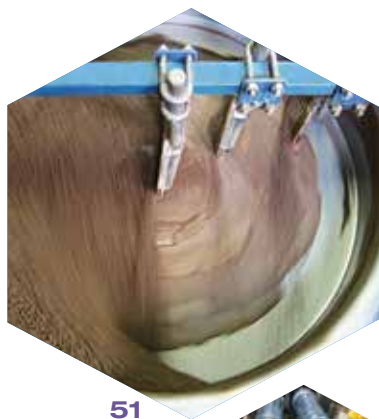
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 BEST PRACTICES
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'Green' chemistry winners

The challenge to create more sustainable and environmentally friendly processes and products is one that many individuals and companies are taking on, and progress continues to be made. Goals such as reduction in raw material use, water conservation, renewable energy expansion and use of non-hazardous materials are some of the areas where efforts abound. In June, the U.S. Environmental Protection Agency (EPA; Washington, D.C.; www.epa.gov) honored four achievements that apply innovative technologies that turn potential problem areas into opportunities by developing safer and more environmentally sustainable processes. Details about the award and selection criteria can be found on the EPA's website. The four winners of the 2019 Green Chemistry Challenge Awards are described here (Source: EPA).

Greener Reaction Conditions Award — Washing Systems, LLC (WSI; Loveland, Ohio; www.washingsystems.com) was honored for developing an alternative to traditional commercial laundering that uses more biodegradable surfactants and eliminates phosphates, alkalis (sodium hydroxide) and nonylphenol ethoxylate from wash operations. The company's trademarked TRUpath technology was commercialized in 2018 and is said to work at lower temperatures than traditional operations, which reduces energy consumption.

Greener Synthetic Pathways Award — Merck Research Laboratories (Rahway, N.J.; www.merck.com) received this award for developing a more sustainable process for manufacturing ceftolozane sulfate — a component of Merck's trademarked antibiotic, Zerbaxa. The innovative change was an implementation of a crystallization-based purification process that is said to reduce material costs by 50% and increase overall yield by more than 50%. The new process is expected to significantly decrease the carbon footprint and energy usage, while also saving water.

Academic Award — Recognition was given to Sanjoy Banerjee, professor of chemical engineering at the City College of New York, and director of the City University of New York Energy Institute, along with Urban Electric Power, Inc., Sandia National Laboratories, Brookhaven National Laboratory, and the Energy Storage Research Program in the Department of Energy Office of Electricity Urban Electric Power, Inc., for developing large-scale, rechargeable alkaline Zn-MnO₂ batteries. An innovative breakthrough in this technology was the use of chemical dopants (Cu ions) to stabilize the MnO₂ cathodes, allowing them to be recharged. A pilot-scale plant has been built by Urban Electric Power, which is commercializing the battery technology. Batteries based on readily available components, such as Zn and MnO₂, could provide a breakthrough for renewable energy expansion.

Small Business Award — Kalion Inc. (Milton, Mass.; www.kalioninc.com) and the Massachusetts Institute of Technology (Cambridge; www.mit.edu) were awarded for commercializing the first microbial fermentation process to produce glucaric acid. Using fermentation in place of traditional routes allows the glucaric acid to be made from a bio-degradable, non-toxic, sugar-based feedstock.

Dorothy Lozowski, Editorial Director

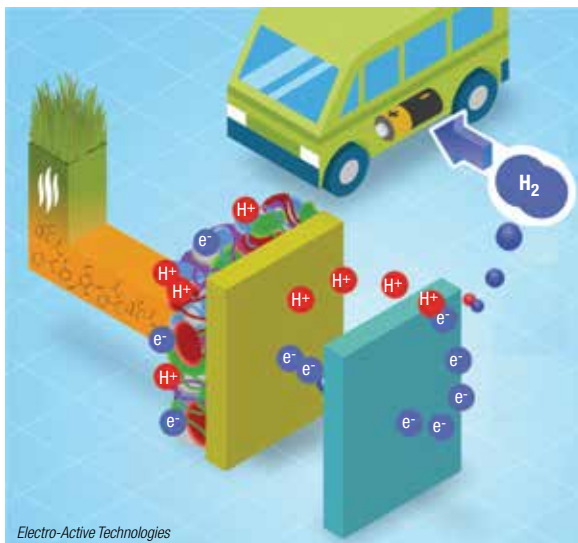


Microbial electrolysis produces H₂ from organic waste

A modular, fuel-cell-like assembly featuring specially developed microbial communities is capable of producing pure hydrogen from a wide range of organic wastes. Developed by startup company Electro-Active Technologies (Oak Ridge, Tenn.; <https://electroactive.tech>), the microbial electrolysis system is now in the prototype stage, and the company has plans for a pilot-scale demonstration in 2020.

The technology offers a way to produce a carbon-free renewable fuel and industrial gas from food waste, and other organic material that might otherwise end up in landfills, generating methane, a potent greenhouse gas. "With microbial electrolysis, we are able to produce pure hydrogen at half the cost of conventional water electrolysis, while also utilizing food waste as a resource," says company CEO Alex Lewis, who co-founded the company with his former advisor Abhijeet Borole after completing his doctoral research project in this area at Oak Ridge National Laboratory (www.ornl.gov).

At the heart of the system is an alternating stack of anodes and cathodes with a carefully cultivated community of microbes growing on one side. A unique feature of the microbial community is the presence of electrogenic bacteria, which are capable of passing electrons outside their cells. In the



electrolysis system, the electrons combine with protons at the cathode to generate hydrogen gas. Other bacteria in the community break down the liquified organic waste into metabolites that are favored by the electrogenic species, Lewis explains. Other elements of the system include a pretreatment step to liquify the organic waste, and a gas purification step to remove inert gases from the H₂ stream.

The company's vision for the technology is to have the modular systems located near sites where organic waste is generated at high rates to convert them into H₂, thereby preventing their disposal in landfills.

Poly-diketoenamines could allow closed-loop plastics recycling

Conventional plastics are difficult to recycle because end-of-life processing generally is either energy-intensive or alters the physical properties of the materials. A team of researchers from the Lawrence Berkeley National Laboratory (Berkeley, Calif.; www.lbl.gov) and the University of California at Berkeley (www.berkeley.edu) is developing polymers that can be de-polymerized using acids at ambient temperatures. Known as poly-diketoenamines (PDKs), the materials are made through condensation reactions between β -triketones and amines, and could allow plastics that can be re-manufactured inexpensively and without a loss of performance.

PDKs are prepared by reacting β -triketones with either aliphatic or aromatic amines to form dynamic covalent diketoenamine bonds. "The reaction between triketones

and amines is spontaneous at ambient temperature," says LBNL research leader Brett Helms, "but can also be conducted in a ball-mill, in the melt, or in solution. It requires no additional chemicals or catalysts," he says.

The resulting polymers can be depolymerized by treating with strong aqueous acids (either H₂SO₄ or HCl) at ambient temperature to yield triketone and amine monomers at greater than 90% yields.

Helms says PDKs can be formulated to access a broad range of physical properties. "It's likely that they are most similar to polyamides and polyurethanes," he notes.

The triketone monomers can be synthesized in a single step from 1,3-dione and polytopic carboxylate compounds, which are both are widely available from petrochemicals processing, but increasingly also from bio-based sources.

Edited by:
Gerald Ondrey

SOLAR DESALINATION

Researchers at Rice University (Houston, Tex.; www.rice.edu) working on nanophotonics-enabled solar membrane distillation (NESMD) have found that concentrating sunlight on small areas of the desalination membrane leads to a non-linear improvement in performance in vapor pressure, which forces more purified (salt-removed) steam through the membrane in less time. NESMD is an enhanced form of membrane distillation that uses sunlight-harvesting nanoparticles to convert photons into heat, and reduces production costs of the system. The Rice team showed that increasing photon intensity in smaller areas boosts the efficiency of their NESMD system by more than 50% compared to a homogeneous distribution of photons over the entire membrane. The sunlight was concentrated into "hot spots" using inexpensive plastic lenses. Conventional membrane distillation works by having hot, salty water flow on one side of the membrane, while cool filtered water flows on the other side. The resulting difference in vapor pressure drives steam (but not salt) from the heated side to pass through the membrane to the cooler, lower-pressure side.

GAS-TO-GASOLINE

On June 28, the world's only natural gas-to-gasoline plant officially opened near Ashgabat, the capital of Turkmenistan. Startup of the plant has proceeded according to plan and the performance-test run is expected to be completed during the coming months. At full capacity, the plant will produce 15,500 barrels per day (bbl/d) of gasoline from natural gas. The plant is based on Haldor Topsoe A/S's (Lyngby, Denmark; www.topsoe.com)

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advanced Tigas technology. The contract to build the plant has been awarded by the national gas company Turkmen gas and is based on Topsoe's proprietary end-to-end technology, Tigas (for more process details, see *Chem. Eng.*, October 2014, p. 11). Utilization is very high with gasoline making up more than 85% of the product stream and 11–13% valuable liquefied gases (LPG). The Tigas process can produce gasoline in compliance with varying national specifications.

Topsoe has supplied license, engineering, catalysts and hardware, such as autothermal reformer (ATR) burner, reactors and boilers for the plant. Kawasaki Heavy Industries was the engineering, procurement and construction (EPC) contractor, and Rönäsans was responsible for erection.

The plant is an important step forward in Turkmenistan's plan to monetize the country's huge natural gas resource — the fourth-largest in the world — and diversify its export potential. In addition, the production will supply the Turkmen home market with synthetic gasoline that complies with the highest environmental standards, contains no sulfur and very little unwanted byproducts.

BIO-BASED PLASTICS

LyondellBasell Industries N.V. (Rotterdam, the Netherlands; www.lyondellbasell.com) and Neste Oyj (Espoo, Finland; www.neste.com) have achieved the first parallel production of bio-based polypropylene (PP) and bio-based low-density polyethylene (LDPE) at a commercial scale. The joint project used Neste's renewable hydrocarbons derived from sustainable bio-based raw materials, such as waste and residue oils. The project successfully produced several thousand metric tons of bio-based plastics that are approved for the production of food packaging and being marketed under Circulen and Circulen Plus, the new

A solvent-extraction approach for desalination of high-salinity brines

Hypersaline industrial wastewater brines are difficult to treat. Current approaches for removing salt from such brines — such as evaporative distillation and reverse-osmosis (RO) — are problematic because evaporation is highly energy-intensive and RO cannot handle salt levels present in hypersaline brines, which can be several times that of seawater.

Now, a research team led by Ngai Yin Yip at Columbia University (New York, N.Y.; www.columbia.edu) has developed a solvent-extraction method they call temperature-swing solvent extraction (TSSE), that dramatically lowers the energy requirements for separating salts from water compared to evaporative distillation, but can also handle very high salt levels. The research could lead to an effective means of treating high-salinity wastewaters from oil and gas production (produced water), as well as landfill leachate, fluegas desulfurization wastewater and concentrated brine from brackish water desalination processes (for areas with no discharge options).

Using solvent-extraction principles, the process works by contacting the brine with a solvent mixture that extracts water from the brine, but that is also immiscible with water, so it can

be easily separated. The Columbia team used three amines — diisopropylamine (DIPA), N-ethylcyclohexylamine (ECHA), and N,N-dimethylcyclohexylamine (DMCHA) — as solvents. "The solvents need to have sufficient hydrocarbon chains to make them separate easily from water, but also hydrophilic functional groups to effectively extract the water," explains Yip.

Then, since the solvent's ability to solubilize water is temperature-dependent (higher temperatures mean less water held), the temperature can be raised from ambient temperatures up to 60–70°C to release the water. The solvent can then be re-used in the process. If zero liquid discharge is the goal, the remaining dewatered raffinate can be distilled to yield solid salts. Since the volume is drastically reduced by the process, managing it with distillation is easier, Yip notes.

The team recently published its work at the laboratory-scale, but is in talks with partners looking to commercialize the technology. At industrial scale, the idea would be to use an industrial liquid-liquid extraction column to separate the salt from water, then use waste heat from another process, or from solar-energy collectors, to raise the solvent temperature and release the salt-free water, Yip says.

Pilot plant slated for a H₂-based process to make DRI from iron-ore fines

The use of direct reduced iron (DRI; sponge iron) and hot briquetted iron (HBI) is expected to continue to grow due to the need to reduce greenhouse gas emissions and the growing number of electric arc furnaces (EAFs) in service worldwide. Currently, all available technologies require agglomeration, like pelletizing, to produce DRI or HBI. An additional challenge that steel producers face is the lower quality of iron ore, resulting in the need to beneficiate the iron ores. In order to progress to CO₂-free steel production, a process using mainly H₂ is most desirable. These considerations are all taken care of by a new process developed by Primetals Technologies, Ltd. (London, U.K.; www.primetals.com).

The new process is said to be the world's first direct-reduction (DR) process for iron-ore concentrates from ore beneficiation not requiring any preprocessing, like sintering or pelletizing. The new technology can be applied to all types of beneficiated ore and particle sizes of 100% smaller than 0.15 mm. As primary reduction agent, the new process uses H₂ from renewable energy or, al-

ternatively, H₂-rich gases from conventional steam reformers or H₂-rich waste gases. This results in a low- or even a zero-CO₂ footprint. The DR plant comes in a modular design with a rated capacity of 250,000 tons per year per module, making it available for all sizes of steel plants. A pilot plant will be set up at voestalpine Stahl Donawitz GmbH, Austria and is due to be commissioned in the second quarter of 2020.

The pilot plant will consist of three parts: a preheating-oxidation unit, a gas-treatment plant and the reduction unit (RU). In the preheating-oxidation unit, fine ore concentrate is heated to approximately 900°C and fed to the RU. The reduction gas H₂ is supplied over-the-fence from a gas supplier. A waste-heat recovery system from the off-gas ensures optimal energy use, and a dry dedusting system takes care of dust emissions. The hot DRI (HDRI) leaves the RU at a temperature of about 600°C, which can be subsequently used in an EAF, or to produce HBI. The pilot plant will be used to verify the process and to serve as a testing facility to provide the data basis for setting up a future industrial-scale plant.

(Continues on p. 8)

family of LyondellBasell circular-economy product brands. LyondellBasell's cracker flexibility allowed it to introduce a new renewable feedstock at its Wesseling, Germany site, which was converted directly into bio-based PE and bio-based PP. An independent third party tested the polymer products using carbon tracers and confirmed they contained over 30% renewable content.

RECYCLING PS

Styrenics Circular Solutions (SCS; Brussels, Belgium; www.styrenics-circular-solutions.com) members Ineos Styrolution (www.ineos-styrolution.com) and Trinseo (www.trinseo.com) have combined resources to advance the development of a commercial-scale plant in Europe for chemically recycling polystyrene (PS). The new plant will be capable of processing up to 50 tons per day of post-consumer PS feedstock. This project advancement follows the promising results of an evaluation study in which SCS, the joint-industry initiative to increase the circularity of styrenic polymers, engaged Agilyx (Tigard, Ore.; www.agilyx.com) to perform tests with samples of post-consumer PS food packaging waste. Agilyx evaluated the composition of the waste feedstock and successfully recycled it back into its original liquid monomer, using its proprietary depolymerization technology. This project demonstrated polystyrene's unique intrinsic capability to be fully recycled.

RECYCLED METHANOL

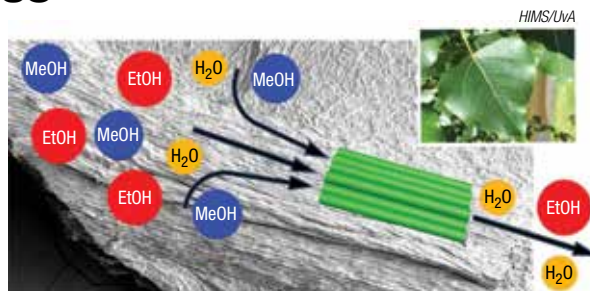
Perstorp Holding AB (Malmö Perstorp, Sweden; www.perstorp.com) will investigate the potential production of recycled methanol, using CO₂ and residual streams, at its Swedish facility in Stenungsund. The Swedish Energy Agency (SEA) will partly finance this feasibility study. This project not only aims to reduce process-related CO₂ emissions but, at the same time, produce a more sustainable, recycled methanol to replace fossil-fuel-derived methanol as a raw material in Perstorp's

(Continues on p. 9)

MOFs that mimic leaves for enhanced performance

Chemists from the research group of Stefania Grecea at the University of Amsterdam's (UvA; the Netherlands; www.uva.nl) Research Priority Sustainable Chemistry have devised a way to enhance the practical performance of metal-organic frameworks (MOFs). By using leaves from the black poplar (*Populus nigra*) as a template, they produced hierarchical porous structures of mixed-metal-oxide materials that can act as a support for MOF crystals. Described in a recent issue of *Applied Materials & Interfaces*, doctoral student Yiwen Tang, in collaboration with David Dubbeldam of the UvA Computational Chemistry group, demonstrated the unique adsorption and separation properties of the bio-inspired design.

The researchers synthesized crystalline zeolitic imidazolate framework (ZIF-8) onto a mixed metal-oxide support TiO₂-SiO₂ (TSO). Using a natural leaf of the black poplar as a template, the TSO support was prepared by a sol-gel process. A layer of crystalline ZIF-8 was then grown on the support to form a ZIF-8@TSO composite. The ZIF-8@TSO composite selectively adsorbs methanol — a property that could be applied for the separation of azeotropic mix-



tures of methanol and ethanol.

Yiwen Tang studied the adsorption properties of the new material for water, methanol and ethanol, and showed that the selectivity varies in the order methanol > ethanol > water. Subsequent molecular simulations performed by Dubbeldam using equimolar ethanol-methanol mixtures showed that methanol adsorption is highly selective in the low-pressure range. Moreover, the material is effective in separating water-ethanol mixtures with ethanol being adsorbed selectively in the low-pressure range, while water is adsorbed selectively at high pressures.

The researchers believe their bio-inspired synthetic approach is highly relevant, not only for molecular separations applications, but also as a general strategy for designing MOF composite materials for other applications, including catalysis and molecular sensing.

A powerful tool to analyze MOFs

An international team, including staff from the Korea Advanced Institute of Science and Technology (Kaist; Daejeon, South Korea; www.kaist.ac.kr), led by Kaist's professor Jeung Ku Kang, has developed a technology to analyze the gas adsorption behavior of molecules of each individual pore of a metal organic framework (MOF). Existing technology is only able to measure the amount of gas molecules adsorbed by the material, without directly observing the adsorption behavior.

The team developed a realtime gas-adsorption crystallography system by integrating an existing X-ray diffraction measurement device that can provide structural information and a gas adsorption measurement device. The system allows the observation of a mesoporous MOF with multiple pores. The team categorized the adsorption behavior of MOF molecules by pore type, achieving the identification of a stepwise adsorption process that was not previously possible to analyze.

The team analyzed how the pore structure and the type of adsorption molecule affect the adsorption behavior to suggest what type of MOF structure is suitable as a storage material for each type of adsorption behavior. Specifically, the team used two MOFs, PCN-224 and ZIF-412 which contain two and three different types of pore, respectively, to generate isotherms of individual pores by combining gas adsorption measurements with in situ X-ray diffraction.

This isotherm decomposition approach provides access to information about the gas uptake capacity, surface area and accessible pore volume of each individual pore, as well as the impact of pore geometry on the uptake and distribution of different adsorbates within the pores.

"By understanding the realtime adsorption behavior of molecules at the level of the pores that form the material, rather than the whole material, we will be able to apply this technology to develop a new high-capacity storage material," says professor Kang.

Insulation mimics polar-bear hair

Scientists from the University of Science and Technology of China (Hefei; <https://en.ustc.edu.cn>), led by professor Shu-Hong Yu, have developed a thermal insulator that mimics the structure of individual polar-bear hairs, and have scaled toward a material made of many hairs. "Polar bear hair has been evolutionarily optimized to help prevent heat loss in cold and humid conditions, which makes it an excellent model for a synthetic heat insulator," says Yu. "By making tube aerogel out of carbon tubes, we can design an analogous elastic and lightweight material that traps heat without degrading noticeably over its lifetime," he says.

Unlike the hairs of other mammals, polar bear hairs are hollow. Each has a long, cylindrical core. The shapes and spacing of these cavities are the source of remarkable heat-holding

capacity, water resistance and elasticity, all desirable properties to duplicate in a thermal insulator.

The scientists manufactured millions of hollowed-out carbon tubes, each equivalent to a single strand of hair, and wound them into a spaghetti-like aerogel block. According to the scientists, the microstructure-derived thermal conductivity and elasticity are strongly dependent on the shell thickness of the interconnected tubes, as well as the aperture of the aerogel. The optimized aerogel can maintain structural integrity after more than one million compress-release cycles at 30% strain and 10,000 cycles at 90% strain. The aerogel's super-elasticity is further confirmed by its fastest rebounding speed of 1,434 mm/s among the traditional elastic materials measured by a standard falling steel ball.

The optimized, minimum thermal conductivity is 23 mW/mK, which performs better than the thermal conductivity of dry air.

production.

Methanol is one of Perstorp's major raw materials, used to produce polyols and formates, the building blocks of many consumer goods, such as coatings and paints, composite materials, detergents, adhesives, cosmetics and synthetic lubricants. Methanol is also used for Perstorp's next generation, phthalate-free plasticizer, Pevalen.

MERCURY-REMOVAL

BASF S.E. (Ludwigshafen, Germany; www.basf.com) recently launched Durasorb HG, a new adsorbent for removing mercury from natural gas. Durasorb HG is a non-regenerable, mixed-metal-oxide adsorbent containing a dispersed and promoted copper-sulfide phase. Durasorb HG is designed to work in wet conditions. The fast kinetics and maximum mercury penetration allow for the most efficient use of the adsorbent bed, says the company.

The addition of a mercury-removal adsorbent complements the Durasorb product line, providing complete pre-treatment solutions for mid-stream gas processors and LNG operators,

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Bowl-shaped electrode enhances CO₂ reduction

An international group of scientists has created a bowl-shaped electrode that can efficiently convert CO₂ into carbon-based fuels and chemicals. The group includes scientists from the University of Bath (Bath, UK; www.bath.ac.uk), Fudan University (Shanghai, China; www.fudan.edu.cn), and the Shanghai Institute of Pollution Control and Ecological Security at Tongji University (Shanghai, China; www.tongji.edu.cn).

Two main obstacles to reducing CO₂ have been poor conversion efficiency and a lack of detailed knowledge about the reaction pathway. The new electrode — made of copper-indium alloy — addresses these challenges, due to its shape and construction. According to the scientists, the bowl-shaped electrode, known as an “inverse opal structure,” works six times faster than standard flat designs.

The shape of the design concentrates electric fields on its hot edges — the rim

of the bowl — which then concentrates positively charged potassium ions on the active sites of the reaction, reducing its energy requirements. The electrode can also be used to study the reaction by measuring the Raman signal, which is higher than that of a typical electrode.

“To improve the efficiency of transforming CO₂ into chemical fuels, it is extremely important to know the reaction pathway and to find the most suitable catalyst,” says professor Liwu Zhang from Fudan University. “Just as plants transform CO₂ into sugar, we are finding a suitable electrochemical ‘leaf’ for CO₂ conversion.”

This study was funded by the Royal Society, the Ministry of Science and Technology of the People's Republic of China, the National Natural Science Foundation of China, and the jointly funded University of Bristol and University of Bath Engineering and Physical Sciences Research Council (EPSRC) Centre for Doctoral Training in Condensed Matter Physics (CDT-CMP). ■

including heavy hydrocarbon removal, BTX (benzene, toluene, xylenes) removal and dehydration.

FINGERPRINT SPECTROSCOPY

Researchers at the Fraunhofer Institute for Applied Solid State Physics (IAF; Freiburg, Germany; www.iaf.fraunhofer.de) have developed a measuring system capable of identifying a wide variety of chemical and pharmaceutical substances remotely and in real time. The core of the system is an extremely fast tunable quantum cascade laser (QCL) operating in the mid-infrared (IR) range (4–12 μm), which is known as the fingerprint region of IR spectra. Based on backscattering spectroscopy, the QCL system not only allows researchers to identify small amounts of chemical substances in real time, but also to continuously control chemical reaction processes.

With the help of researchers at the Fraunhofer Institute for Photonic Microsystems (IPMS; Dresden, Germany; www.ipms.fraunhofer.de), IAF has developed a compact and robust laser source with which the whole wavelength range of the QCL emitter can be scanned within a millisecond. □

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Plant Watch

Oxea to build new carboxylic acids plant in Germany

July 6, 2019 — Oxea (Monheim am Rhein, Germany; www.oxea-chemicals.com) is building a new world-scale production plant for carboxylic acids in Oberhausen, Germany. When brought onstream by the end of 2021, it will double the current production capacity for isononanoic acid and increase Oxea's total production capacity for carboxylic acids by more than 30%.

Total starts up biorefinery in southeast France

July 3, 2019 — Total (Paris, France; www.total.com) has started up production at the La Mède biorefinery in southeastern France, with the first batches of biofuel coming off the line. It is the final step in converting a former oil refinery into a new energies complex. Launched in 2015, the project represents a capital expenditure of €275 million. The biorefinery has a capacity of 500,000 metric tons per year (m.t./yr).

Lenzing Group builds world's largest lyocell fiber plant in Thailand

June 26, 2019 — Over the next few years, Lenzing Group (Lenzing, Austria; www.lenzing.com) plans to invest more than €1 billion in new production facilities for lyocell fibers. The first expansion phase of this growth plan, the construction of a lyocell fiber production plant in Prachinburi, Thailand, has now been approved. The plant will have a capacity of 100,000 ton/yr and feature investments of approximately €400 million.

McDermott awarded *p*-xylene technology contract in China

June 13, 2019 — McDermott International, Inc. (Houston; www.mcdermott.com) has been awarded a sizeable (\$1–50 million) technology contract by Ningbo Union King Polyester Material Ltd. for the technology license, process design engineering and operator training services for a large-scale, grassroots 1,600,000-ton/yr *p*-xylene plant at Ningbo Union King's petrochemicals facility in Ningbo, China.

Orion to expand production capacity for gas blacks

June 13, 2019 — Carbon-black producer Orion Engineered Carbons S.A. (Houston; www.orioncarbons.com) says it will expand its production capacity for gas blacks at its Cologne (Kalscheuren) plant, Germany.

Eastman expands capacity for DEHA at Louisiana facility

June 13, 2019 — Eastman Chemical Co. (Kingsport, Tenn.; www.eastman.com) announced the successful completion of a debottlenecking of its diethylhydroxylamine (DEHA) unit in St. Gabriel, La. The debottlenecking has resulted in a 15–20% increase in capacity.

Wood secures contract for greenfield petrochemicals project in Oman

June 11, 2019 — Wood plc (Aberdeen, U.K.; www.woodplc.com) has been awarded a new contract by Duqm Refinery and Petrochemicals Industries Co. (DRPIC) to provide FEED (front-end engineering design) for a proposed onshore petrochemicals facility at the Special Economic Zone Area Duqm (SEZAD) in southern Oman. Wood has already delivered associated studies for the facility, which will include a world-scale steam cracker unit and production facilities for H₂, syngas, methanol and other petrochemicals.

Wacker expands silicone elastomer production in China

June 10, 2019 — Wacker Chemie AG (Munich, Germany; www.wacker.com) inaugurated a new production line for silicone elastomers at its Zhangjiagang site in China. With an annual capacity of several thousand metric tons, the facility will help support Wacker's future growth path in China and improve the availability of high-consistency silicone rubber (HCR) in the Asia-Pacific region. The expansion measure represents a lower double-digit-million-euro investment.

Babcock & Wilcox awarded contract for cooling tower upgrade in Belgium

June 6, 2019 — Babcock & Wilcox SPIG, Inc. (SPIG; Paruzzaro, Italy; www.babcock.com/spig) has been awarded a contract to provide cooling-tower upgrade services for BASF Dow HPPO Production BVBA's propylene oxide manufacturing facility in Antwerp, Belgium. SPIG will develop customized solutions to improve the performance of the plant's existing cooling towers. SPIG also will replace eight existing cooling-tower cells with new units. SPIG is scheduled to complete its work in the second quarter of 2020.

Ineos to invest \$2 billion in Saudi Arabia

June 4, 2019 — Ineos (London, U.K.; www.ineos.com) signed a memorandum of understanding with Saudi Aramco and Total to build three new plants as part of the Jubail 2 com-



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plex in The Kingdom of Saudi Arabia. A new 425,000 m.t./yr acrylonitrile plant will use Ineos' technology and catalyst, and will be the first plant of its kind in the Middle East when it starts up in 2025. Ineos will also build a 400,000 m.t./yr linear alpha-olefin plant and associated world-scale poly-alpha-olefin plant. These units will begin production in 2025.

Mergers & Acquisitions

Aspen Tech announces two acquisitions

July 12, 2019 — Aspen Technology, Inc. (Bedford, Mass.; www.aspentech.com) has signed an agreement to acquire Mnubo Inc., a Montreal-based provider of purpose-built artificial intelligence (AI) and analytics infrastructure for the internet of things (IoT). Mnubo enables industrial companies to assemble and deploy AI-driven IoT applications quickly, at enterprise scale. AspenTech has also acquired Sabisu Ltd., a U.K.-based company that provides a flexible enterprise visualization and workflow solution to deliver realtime decision support.

Outotec to merge with Metso Minerals

July 4, 2019 — Metso Corp. (Helsinki, Finland; www.metso.com) and Outotec Oyj (Espoo, Finland; www.outotec.com) have agreed to combine Metso Minerals and Outotec to create a leading company in process technology, equipment and services serving the minerals, metals and aggregates industries. The combined company, comprising Metso Minerals and Outotec (but excluding Metso Flow Control), will be named Metso Outotec. With this transaction, Metso Flow Control will become a separately listed independent flow-control equipment and services company under then of Neles. Its headquarters will be in Vantaa, Finland.

Pfizer will acquire Array BioPharma

June 17, 2019 — Pfizer Inc. (New York; www.pfizer.com) and Array BioPharma Inc. (Boulder, Colo.; www.arraybiopharma.com) have entered into a definitive merger agreement under which Pfizer will acquire Array, a commercial-stage biopharmaceutical company focused on the discovery, development and commercialization of targeted small-molecule medicines to treat cancer and other diseases. Pfizer has agreed to acquire Array for \$48 per share in cash, for a total enterprise value of approximately \$11.4 billion.

DuPont becomes an independent company

June 10, 2019 — DuPont de Nemours, Inc. (DuPont, Wilmington Del., www.dupont.com) announced on June 3 its debut as an independent company following the successful separation of its Agriculture Division through the spin-off of Corteva, Inc. The company was formerly known as DowDuPont Inc. DuPont has a presence in over 70 countries, and operates approximately 170 manufacturing sites, over 10 global R&D centers and 10 global innovation centers. ■

Gerald Ondrey

Increasing the Reliability of Valves Through Design

The latest valves are designed to last in challenging chemical applications, increasing uptime and safety

As operational efficiency and safety continue to be top priorities in the chemical process industries (CPI), processors are demanding increased reliability from their equipment, and valves — whether large process control valves or small pilot, pressure reducing or specialty valves — are no exception to this rule. Fortunately more robust valve designs, as well as smarter valves and accessories, are boosting the performance of all types of valves, even in the harshest of environments.

Reliability and safety are obviously important in the CPI, whether it's small batch processing or continuous processing. "Usually when the batch is small, it's expensive feed-stock they [the manufacturers] are moving, which means the monetary loss is high if there is contamination of the process or leakage and loss of material caused by faulty valves," says Gabe Boltmew, product marketing manager for Emerson Automation Solutions (Florham Park, N.J.; www.emerson.com). "In large, continuous processes, if a valve fails and causes the process to shut down, there's very expensive downtime and loss of production associated with that failure, so reliability of valves is a concern for any chemical processor."

However, while reliability is a top priority, it's often difficult to achieve due to the challenging chemical processing environment. Not only are processors running highly corrosive or aggressive media, but there may be high temperatures, high pressures and solids content, as well as harsh clean-in-place (CIP) and steam-in-place (SIP) procedures, making it difficult to find a valve so-



FIGURE 1. Model 521 is a sliding stem, globe-style, bellows-sealed, pneumatically actuated control valve designed to provide long-term performance and maximum corrosion resistance in pure chemical service

lution that will last in these extreme conditions. And, when you throw safety concerns like fugitive emissions or leaks of aggressive media, high pressures and outgassing into the mix, the stakes become higher. "It really comes down to mitigating risk. Failure of valves in the chemical industry can result not only in loss of profit, but also in damage to the environment or death to employees. These dangers exist not just from the chemicals being handled, but also from the violent force that may occur if there's an explosion," says Anders Ryan, technical sales manager with Plast-O-Matic Valves (Cedar Grove,

N.J.; www.plastomatic.com).

For all these reasons, valve manufacturers are offering new designs and smarter equipment to help enhance reliability of valves, which in turn increases safety, uptime and efficiency within chemical facilities.

More robust valve designs

"There are significant challenges when it comes to longevity of valves in chemical processes," says Dan Ray, director of EPC, with Cashco (Ellsworth, Kan.; www.cashco.com). "Whether it's chemical compatibility, pH, velocity or other factors, difficult phenomena exist within chemical plants, making it tough to find a valve that will last in the chemical processing environment."

Ray says valve manufacturers are rising to the challenge via the use of new materials and designs. "As the chemical industry continues to handle new chemicals and the aggressiveness of those chemicals increases, we are seeing new materials introduced and new designs in valve bodies, allowing valves to become more compatible with these environments."

He points to Cashco Model 521 (Figure 1) as an example. "This valve was designed for processes that deal with very corrosive materials or where permeation is an issue and lined pipes are required," he says. "However, it's not a lined control valve, which typically feature a spray-on material or very thin film." Instead, Model 521 is a sliding stem, globe-style, bellows-sealed, pneumatically actuated control valve designed to provide long-term performance and maximum corrosion resistance in pure chemical service. It is designed so that all wetted internal parts are



FIGURE 2. When the QuadroSphere ball cycles, the recessed surfaces allow solids to be flushed from the cavity, preventing buildup of the solids around the seat rings and bearings

machined from a solid block of iso-statically compacted, virgin tetrafluoroethylene (TFE), ensuring maximum density and the lowest possible permeability. An additional design benefit is that the wall-thickness integrity is ensured as a result of the TFE body being internally machined after it is secured in a cast 304 stainless-steel body shell, preventing distortion problems related to the plastic stability of TFE.

Val-Matic (Elmhurst, Ill.; www.valmatic.com) is also working on designs that enhance performance in difficult applications. "One of the most difficult applications for a ball valve is one that sees grit, solids or abrasive media, as it tends to wear and erode the sealing properties of the valve quickly," says Stephen Dalton, director of engineering with Val-Matic. In response to this challenge, the company developed the QuadroSphere (Figure 2). "In traditional ball valves, there are certain areas of cavities that tend not to get a lot of flow through them and, therefore, collect fine and abrasive grit, which creates problems. So, instead of using a traditional sphere-shaped ball, we've machined away portions of the ball, creating recessed areas."

The surfaces of the full-port ball that are non-essential to sealing have been recessed in all four quadrants, creating additional flow paths that allow the flow and particulates

to move freely above, below and around the sides of the ball when moving from closed to open position. Seat ring contact to the ball has minimal contact area, which reduces wear and operating torques due to less friction.

The design is self cleaning. Typical ball valves allow liquids and solids to be trapped within the body/ball cavity, which results in solids accumulating around the ball, causing clogging

and damage to the seating surfaces. However, when the QuadroSphere ball cycles, the recessed surfaces allow solids to be flushed from the cavity, preventing buildup of the solids around the seat rings and bearings.

New designs are also being developed to enhance safety, as well as reliability. "When you're dealing with very aggressive chemicals, safety is a priority in the plant. If you get a leak of aggressive chemical, it could



FIGURE 3. Multi-port block valves tie in all the connectors, piping and two-way valves to create a modular block design, increasing safety and reducing potential leak points

harm the environment and/or the operators using the system. So valve safety often translates into having as few potential leak points into piping, connectors and valves as is possible,” says Jeff Borchers, industrial team leader and industrial product manager with GEMÜ, USA (Atlanta, Ga.; www.gemu-group.com).

“For this reason our multi-port block valves are becoming popular,” says Jared Godfrey, team leader and product manager for the semiconductor division of GEMÜ, USA. “We can tie in all the connectors, piping and two-way valves to create a modular block design. Not only does this increase safety and reduce potential leak points, but combining functions in one block reduces the residual volumes of media in the system, optimizes flow and improves drainage, which is also beneficial in high-purity applications, such as semiconductor manufacturing (Figure 3).

Often used as safety mechanisms in process plants, air release, pressure relief, backpressure and degassing valves are also getting design renovations to further enhance safety and performance. “There are several challenges associated with piping and valve systems for the chemical industry,” says Plast-O-Matic’s Ryan. “One would be outgassing of a fluid. If you get air into your piping system, you create transient pressure bubbles that can then move around, find the weakest point and cause the piping systems to fail. Also, air can impede the flow of fluid and decrease



FIGURE 4. Series CARD releases air at startup and then closes it so the system can safely and effectively operate

productivity. Pressure-relief valves, pressure regulators and backpressure valves are designed to reduce risk and mean time between failures, as they were made to control pressure and outgassing of rogue air in a piping system, thus eliminating major safety risks.”

For this reason, Plast-O-Matic offers a variety of redesigned air release/degassing valves. Among the newest offerings is a combination valve. Series CARD (Combination Air Release and Degassing Valve) releases air at startup and then closes so the system can safely and effectively operate (Figure 4). In addition, the valve is designed to release trace amounts of air that occur during operation. “Air might become entrained in the fluid or be sucked in from a pump or the chemical will outgas itself and this air can cause problems,” says Ryan. “This combination valve will distinguish between the liquid and the gas and allow the gas to escape. It’s a little valve that does the work of two separate valves.”

Specialty valves also are seeing redesigns that make them more reliable and efficient. “The hold up volumes and clean-ability of hygienic valves used in the biopharm industry are extremely critical, because these applications use living organisms so it’s very important that the systems, including the valves, are very sterile.”



FIGURE 5. The EnviZion valve eliminates the effects of thermal cycling. The active sealing technology, which employs a thermal compensation system, provides a reliable seal that won’t degrade over time

Most systems in this industry are designed for clean-in-place and sterilize-in-place processes. “This means valves used in these applications must be able to withstand not only the process, but the variety of chemicals and thermal cycling associated with CIP and SIP. This requires materials of construction and valve architecture that will allow for these chemicals and temperature ranges,” explains Rick Kovacs, director of research and development, with ITT Engineered Valves (Lancaster, Pa.; www.engvalves.com). “The other challenge is, operationally, hygienic diaphragm valves are critical but they won’t last forever, necessitating periodic replacement. But, maintenance for diaphragm valves can be lengthy and people tend to make mistakes, increasing the likelihood of failure.”

To handle the chemicals, thermal cycles and maintenance challenges, ITT Engineered Valves developed the Pure-Flo EnviZion valve (Figure 5), says Paul McClune, product manager with the company. The valve was designed to help users install, operate and maintain their valves more efficiently via a mount-and-turn design that allows for quick and easy valve disassembly. No tools are required for valve installation and diaphragm replacement and fasteners have been eliminated. The EnviZion valve also eliminated the effects of thermal cycling. The active sealing technology, which employs a thermal compensation system, provides a reliable seal that doesn’t degrade over time. The seal is maintained over varying operating conditions, eliminating the need to adjust fasteners after ther-



FIGURE 6. Fisher 667 size 30i through 76i actuators incorporate an integral air passage that eliminates the need for external tubing and fittings when paired with a DVC2000 or DVC6200

mal cycling. In addition the valve improves clean-ability by reducing the potential for fluid entrapment. The valve body and diaphragm create a seal on the leading edge of the D-section, preventing fluid from getting into an area, which would otherwise be difficult to clean and possibly lead to process contamination.

Smarter valves and accessories

Recently, there has been an introduction of smarter, more automated valves and accessories, such as positioners and limit switches, which allow users to open and close those valves from a central control room, says Jim Sullivan, valve divisional director with Wolseley (Newport News, Va.; www.wolseleyindustrialgroup.com). "The accessories are often simple to plug in or wire back to a control room and provide data to the user so they know how many times that valve has opened or closed. This information is used to increase reliability because it provides data that can be used for diagnostic purposes. For example, users can study the data and identify trends, so they know that at the millionth cycle, it's time for them to tighten packing or replace the valve during the next turnaround."

Nathan McCormick, director, chemical process industries with Fisher Valves for Emerson Automa-



FIGURE 7. The 546 PRO ball valve features a sensor in the ball that allows users to see what's going on inside the valve itself, not the actuator, for accurate pressure and temperature measurements

tion Solutions (Marshalltown, Iowa; www.emerson.com), agrees: "Valves are becoming smarter as improvements in sensors, diagnostics and predictive algorithms allow us to capture more of the behavior of the device and provide information on both relative health and concrete steps that can be taken to correct any issues."

He adds that valves form a critical part of Emerson's industrial internet of things (IIoT) strategy due to their direct contact with and impact on process fluids. "For example, there are dozens of diagnostic and information parameters available from every control valve equipped with a digital valve controller, such as the DVC6200," he says (Figure 6). "The biggest issue in capitalizing on that information in plants today is the sheer amount of data available. At Emerson, we have new services available to provide valve condition monitoring on an ongoing basis, allowing users to cut through all the data and get detailed, actionable reports from our valve experts on the exact condition of all their monitored assets, which leads to better maintenance decisions, improved process uptime and efficiency."

Other valve manufacturers, such as GF Piping Systems (Irvine, Calif.; www.georgfischer.com) are adding "smarts" to their valves and accessories, as well. For example, the EA25 electric actuator has been upgraded to include the newest sensing technology. "This actuator uses an inductive sensor that tells the ac-



FIGURE 8. The Redundant Control Systems (RCS) provides complete functional safety with enhanced reliability. It is a pilot valve system with no single point of failure that could result in unwanted closure of the process valve

tuator the position instead of using cams that can corrode. The addition of solid-state control allows for push-button end stop adjustments and a seven-segment display shows fault indication," says Jon Parker, market segment manager, chemical process industry, with GF Piping.

The company also released the 546 PRO ball valve (Figure 7). "We added a sensor in the ball that allows users to see what's going on inside the valve itself, not the actuator," says Jeff Sixsmith, product manager for valves and actuation, with GF Piping. "This latest technology allows users to read pressure and temperature inside the valve, as well as the position of the valve."

And, intelligence has also been added to valves to increase safety and reliability in critical applications, says Emerson's Boltnew. "In critical applications, reliability of the valve is important. If the valve is open and it should be closed, it could be a major safety or process issue, so they need to monitor that information in the control room, which means they need reliable products that provide feedback."

For such applications, ASCO's Redundant Control Systems (RCS) (Figure 8) provides complete functional safety with enhanced reliability. It is a pilot valve system with no single point of failure that could result in unwanted closure of the process valve. The system achieves a high level of process safety and reliability by using a redundant, fault-tolerant architecture, high diagnostic coverage and automated testing. The RCS is fit for use in SIL 3 applications and helps to reduce trip rates.

Joy LePree

Focus on Pipes, Tubing and Fittings

Cortec



Plastic caps with corrosion inhibitors protect pipe in transit

The CorroLogic CorrPlug caps (photo) protect pipe ends, pipe threads and other tubular objects from corrosion, mechanical damage and intrusion (by foreign objects) during storage and shipping. These pipe caps are constructed from heavy-wall black polyethylene that contains proprietary, vapor-phase corrosion inhibitors. They are designed for easy installation and removal, which helps to reduce labor needs. During humidity testing, pipe threads equipped with these caps showed a significant advantage in corrosion resistance compared to those capped with regular plastic caps that contain no corrosion inhibitors, says the company. These caps are made to order in most standard NPT pipe sizes, ranging from 0.25 to 65 in. in dia. They protect carbon steel, stainless steel, copper, brass and aluminum pipes. — Cortec Corp., St. Paul, Minn.

www.cortecvci.com



Tuf-Lok International

These pipe and tube couplings are self-aligning

The Tuf-Lok ring-grip pipe couplings (photo) are heavy-duty, self-aligning couplings that are suitable for either high-pressure (to 150 psig) or full vacuum-rated applications. These couplings install quickly and easily, reducing installation costs. They are available in 2-in. dia. (50-mm) through 10-in. dia. (250-mm) pipe sizes. They are made for use on plain-end pipes, regardless of pipe wall thickness. No machining or grooving is required to maintain pipe integrity. They are designed to be self-grounding, vibration-resistant and leak-proof. Numerous gasket materials are available to help operators meet desired design conditions for food-grade, higher-temperature and special chemical-resistant applications. They install easily, making them ideal for situations that require frequent assembly



GF Piping System



Alfa Laval Kolding

and dissassembly, says the company. — Tuf-Lok International, Madison, Wis. www.tuflok.com

These piping components withstand harsh chemicals

The ChlorFIT piping system (photo), made from Schedule 80 chlorinated polyvinyl chloride (CPVC), is designed to provide a long-lasting, cost-effective alternative to copper and stainless-steel piping for applications that require transport of corrosive fluids. This helps to reduce maintenance and replacement costs, compared to traditional installations, says the company. The pipes and fittings are extruded or molded from premium-grade CPVC compound, which has proven resistance to nitric acid, sodium chloride, sulfuric acid, phosphoric acid and hydrochloric acid, as well as many other corrosive fluids. This material also has superior fire-resistant qualities, and holds the ICC-ES PMG E84 25/50 plenum fire rating. Unlike many other thermoplastic piping options, ChlorFIT can operate at temperatures from 32–200°F (higher than many other plastic piping systems), and is more lightweight and easier to handle than metal piping solutions. Pipes are available in sizes from 0.25 to 24 in. dia., and joining is accomplished with solvent welding, threaded joints and full-pressure flanges. — GF Piping Systems, Irvine, Calif.

www.gfps.com

These tubes and fittings meet rigorous high-purity needs

This company's comprehensive family of DIN tubes and fittings (photo) is specifically designed for food, dairy, beverage, personal care, biotechnology and pharmaceutical applications. All products are designed to have crevice-free interiors and secure, self-aligning joints, and they meet ISO 9001 (quality) and ISO 14001 (environmental) standards. The product family includes unions, clamp fittings, flanges, bends, tees, reducers and tubes that reduce corrosion resis-

Note: For more information, circle the 3-digit number on p. 58, or use the website designation.

tance. Reliable dimensional accuracy and structural integrity make them easy to install, says the firm. — *Alfa Laval Kolding A/S, Kolding, Denmark*
www.alfalaval.com

Use quick-release couplings in food-related applications

The stainless-steel fittings in the Innoxline product family (photo) were developed for use in hygiene-sensitive areas. Four versions of the quick-release, push-in couplings are available: round, triangular, hexagonal and octagonal. An optional shutoff on both sides offers enhanced safety. The latest products in the family are coded, quick-release couplings that are designed for compressed air. The connectors are manufactured from stainless steel 1.4404, are equipped with FDA-compliant seals, and prevent the penetration of contamination through the outer contour in the connected state, making them suitable



Eisele Pneumatics

for use in food-related environments. The durable connectors are designed for operating pressures from 0.5 to 1 bar. — *Eisele Pneumatics GmbH & Co., Waiblingen, Germany*
www.eisele.eu

System enhances safety when changing connectors

The patented BFM Connector flexible fitting and connector system allows for a snap-fit installation that requires no tools. This creates a safer alternative to traditional hose-clip type connectors, says the company, thereby eliminating the risk of injury to workers. A recent innovation from the company — the BFM Pneumatic Monitoring System (photo) — pumps pressurized air between the silicone cuff of the BFM connector and the spigot in which it sits. An air-line sensor immediately detects if this outward pressure is released as the connector cuff starts to be removed, setting off an alarm and shutting off any moving parts below. This enhances safety for workers who are removing connectors in these types

of positions. The standard option is waterproof and dustproof (to IP65 level), and an ATEX-compliant version is also available. The system has a tamper-proof gage and can be used as a positional sensor to ensure all connectors are installed correctly at all times. — *BFM Global Ltd., Houston*

www.bfmfitting.com



BFM Global

These seals avoid damage by 'explosive decompression'

Elastomer seals are used to create a barrier to prevent the escape of gaseous media from valves, pipes, fittings or pig traps. When the pressure of highly pressurized gases falls to a very low level within a short period of time, the seal can become damaged by a process caused explosive decompression (creating tearing or blistering of the surface; photo, p. 20). This company has developed seven advanced

compounds that provide superior resistance against explosive decompression. All of these new compounds fulfill the Norsok Standard M-710 requirements, and several fulfill the API 6A and 6D standard and the TM 0297 and TM 0187 from the National Assn. of Corrosion Engineers. — *Firma C. Otto Gehrckens (COG) GmbH & Co. KG, Pinneberg, Germany*

www.cog.de



Firma C. Otto Gehrckens (COG)

This simulation and sizing tool has added new capabilities

This developer of simulation and sizing tools for piping has released Version 4.83 of Pass/Start-Prof. The latest version contains significantly broader support for a diverse array of international standards related to stress analysis and sizing of piping systems, says the company. This version also extends the piping-support database delivered with the program, show-

casing data related to both variable springs and constant-load springs. — *PSRE Co., Montreal, Canada*
www.passuite.com

Corrugated tubing provides advantages distributing gases

MediTrac is said to be the world's first corrugated medical tubing (CMT; photo) for distribution of medical gases (including medical air, oxygen, nitrogen, nitrous oxide, carbon dioxide) and medical vacuum. Unlike rigid copper tubing that must be installed in numerous brazed sections using elbow joints to accommodate a facility layout, MediTrac semi-rigid tubing installs in a single, bendable length that can be routed around existing structures. Made from copper alloy and sold in continuous-length rolls, MediTrac includes a fire-retardant jacket and axial swaged brass fittings. It eliminates hot work, says the manufac-



OmegaFlex

turer. It is available in sizes from 0.5 to 2 in. dia. — *OmegaFlex, Inc., Exton, Pa.*
www.omegaflexcorp.com

Platinum-cured silicone tubing handles temperature extremes

AdvantaSil Ultra Low Temperature Silicone Tubing products provide platinum-cured tubing to support single-use, cold storage and bulk-drug transport of high-value cell and drug products produced during pharmaceutical and biopharmaceutical manufacturing. The products withstand temperatures from -112°C to 175°C, and are available as bulk tubing, and within single-use assemblies with molded T-shaped, Y-shaped connectors, crosses and reducer connectors, and as bag assemblies and container closures. The tubing can be sterilized by autoclave or gamma irradiation. It is available in five sizes ranging from 1/8 to 1/2 in. inner dia. — *AdvantaPure, div. of NewAge Industries, Southampton, Pa.*

www.newageindustries.com

Suzanne Shelley

Selecting a Heat-Transfer Fluid Supplier

Department Editor: Scott Jenkins

Lean workforces are the norm in current plant environments. In the context of heat exchange systems, the current situation amplifies the need to select a heat-transfer fluid supplier with the expertise and technical resources to handle non-routine circumstances. This one-page reference outlines questions that operating companies should consider when selecting a supplier.

Product options

Products backed by years of history and consistency of published data carry less technical risk. Early in project cycles, fluid selection often requires close collaboration with fluid experts to select the optimal chemistry to meet heat-duty demands, provide longevity with low lifecycle costs, and limit risks for operational and process safety. Allowing a heat-transfer system to be a testing ground for inexperienced vendors or products that are unproven in the given application presents significant risks. Suppliers with broad experience with established fluids in varying applications mitigate that risk. Consider the value of using a supplier with a large portfolio, proven technical data and properties, and a variety of chemistries from which to choose.

Distribution network

Each day of lost production while waiting for heat-transfer fluid to arrive can be extremely costly, so the value of a good distribution network that will provide product sourcing from strategically located distribution points is critical. The ability to provide products to all key markets and regions is the mark of a supplier invested in customer support. It is also a leading indicator of the supplier's ability to provide emergency supplies of fluid when needed.

Customer support

Ensure the supplier provides 24/7 customer service access. Immediate accessibility empowers the supplier's team to respond quickly to a user in need. They must also be able



Beyond fluid, choosing a supplier with reliable service and supply is key

to ensure the fluid can be off-loaded into the system without delay. This requires experienced customer service representatives who ask the right questions and understand necessary equipment, such as pumps, lengths of hose, and proper fittings. Fluid users should be able to leverage these key resources at no added cost.

Product quality

Reliable fluid quality is key to meeting performance expectations. Failing to meet requirements may not only cause the fluid to fail to work as intended, but could also result in costly added downtime or added safety risks to personnel. Certificates of analysis indicate the required specifications that must be met by the fluid manufacturer. When choosing a manufacturer, consider the added value of using only those that have ISO 9001 quality-management-system certification or equivalent. This can protect the user from any potential deviations. These quality systems carry considerable cost to maintain by the manufacturer, so the added assurance to users is of great value.

Technical expertise

When facing a potentially costly problem, having a dependable source of expertise is critical for finding an effective resolution while saving valuable time. This can only be offered by a fluid manufacturer with adequate staff to manufacture and support problem-free, high-quality products. When considering candidate fluid suppliers, ensure they offer the technical expertise needed. Pay special attention to the number of support engineers on staff, their tenure, and evidence of

practical experience in industry leadership via publications, conference presentations and webinars, industry-standard development, and more. A well-staffed team with the right expertise can help identify and resolve issues faster, restoring heat transfer fluid and system integrity more quickly while avoiding a costly trial-and-error approach.

Support services

During routine operation, systems should continue to benefit from the support services available from reputable suppliers, including fluid-quality monitoring by competent laboratories that test the key quality parameters of a fluid for indicative trends and provide early-alert warnings to identify potential problems before they develop. There are several aspects of support that should be considered: Get design and modification review support from the fluid experts in modifications to a heat-transfer fluid system; get support on fluid disposal; get product training, start-up support, and troubleshooting support.

Reputation

To ensure you receive all the benefits mentioned, choose a preferred fluid supplier with a solid reputation. When making a decision, gather testimonials from heater and equipment manufacturers and other fluid users. The best fluid manufacturers understand the value they can create for growing business and will invest their resources into maintaining their reputation. This is accomplished through prompt and excellent customer support, creating the win-win environment heat-transfer-fluid users desire. ■

Editor's note: The content in this column was contributed by Eastman Chemical Co.

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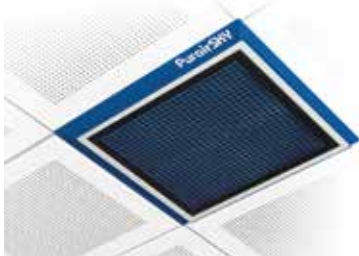
New Products

Softing Industrial Automation



High plant availability and simplified Profibus integration

This company just released version 1.20 of its Modbus-to-Profibus gateways (photo), adding redundancy for critical process-control applications, and adding XML import for simplified integration into Schneider Electric engineering systems. The Modbus-to-Profibus Gateways mbGate PA, mbGate PB and mbGate DP enable the direct integration of Profibus PA and DP segments into Modbus/TCP systems. They act as Modbus server and Profibus master and connect up to four Profibus PA segments, as well as one DP segment with Modbus TCP. Version 1.20 now supports the operation of two redundant gateways in combination with two redundant Modbus controllers. In this way, system availability is ensured even in the event of a connection failure. — *Softing Industrial Automation GmbH, Haar, Germany*
<https://industrial.softing.com>



Air Science



Phoenix Contact

Protect R&D personnel with this ceiling-mounted filtration unit

Purair SKY ceiling-mounted filtration units (photo) are designed to protect laboratory personnel and the environment in areas where hazardous substances are handled. These units feature a dynamic-filtration chamber with a sliding filter clamp that allows for simple, quick filter changes. Units come with an epoxy-coated steel support frame with LED lighting and wall-mounted controls. An electrostatic pre-filter helps trap additional contaminants and increase filter life. Central to the design of the Purair SKY Series is the Multiplex Filtration System developed to ensure universal protection in the work environment. — *Air Science, Fort Myers, Fla.*
www.airscience.com



GMI

robust, splash-proof-, and ultraviolet (UV)-resistant housing is rated for IP66 protection and is perfect for direct installation outdoors and can be used for temperatures in the -25 to 55°C range. The completely pre-wired control box with integrated power-supply unit, surge protection, selected wireless module and I/O extension modules enables intuitive commissioning and makes configuration easier. — *Phoenix Contact GmbH & Co. KG, Blomberg, Germany*
www.phoenixcontact.com

This multi-gas instrument has been enhanced

The PS200 portable multi-gas detection instrument (photo) now features some new enhancements. One such improvement is a powerful new data-logging capacity that will enable users to capture all relevant calibration and session data over a six-month period. This increased capacity will improve users' access to relevant data while enabling quicker decisions to be made. Another helpful addition is the new quick-press field-calibration mode, which saves time by simplifying the field-calibration process. Users can also visualize short- and long-term exposures to CO and H₂S, enabling them to quickly determine current exposure rates and take appropriate action. — *GMI, a company within the 3M Personal Safety Division, Renfrew, Scotland*
<https://gasdetection.3m.com>

A new filter press for cost-effective filtration

For standard filtration applications, when a short delivery lead-time and safe, reliable operation are priorities, the new FP-S filter press (photo) offers efficient solid-liquid separation. It is available in a wide range of configurations, and is backed by the company's technical services to ensure reliable process performance and long equipment lifetime. The new FP-S Filter Press offers the same safety, reliability and quality as the company's other filtration solutions, but is designed for less demanding applications that do not require product tailoring to meet the exact need of each process. The FP-S filter press is suitable for a broad

Modular wireless solution for outdoor use

The new Radioline outdoor box (photo) can be installed directly outdoors for quick and easy wireless transfer of input/output (I/O) signals and serial data. Users can select the wireless modules (the alternatives are 868, 900 or 2,400 MHz) and the type and number of I/O extension modules when selecting the correct unit. The



Outotecj

range of applications, including filtration in bulk mining, tailings, metallurgical refineries, industrial minerals, food, pharmaceuticals and biotechnology. It is available with filtration areas ranging from 1 to 1,000 m² of filtration area. — *Outotec Oyj, Espoo, Finland*
www.outotec.com

A new compressor series for high-pressure requirements

The air-cooled Orkan series (photo) comprises oil-lubricated piston compressors and gas compressors of up to 110 kW for final pressures of up to 500 barg. Booster solutions with inlet pressures of up to 16 barg are also covered. The new series is expected to enter the market within the first quarter of 2020. The Orkan series is based on a versatile, modular system. Various designs are ready for handling special requirements. There are hermetically gas-tight and explosion-proof versions for helium, natural gas and hydrogen. In the hermetically gas-tight compressors, the company uses a new type of magnet coupling for the first time. It not only guarantees absolute gas-tightness but is also extremely low-maintenance and operates with maximum reliability, says the company. — *J. P. Sauer & Sohn Maschinenbau GmbH, Kiel, Germany*
www.sauercompressors.com

Interlock combines maximum force in a compact package

The new HS1T interlock switch with solenoid (photo) delivers an industry-leading 5,000 N of locking force, with many features included to maximize protection in machine and equipment guarding applications. Such interlock switches are incorporated into machinery and equipment to both monitor and lock gates, doors and similar access points. Many of these applications endure high vibration, thrown debris, physical abuse and even bypass attempts, so they must have a high locking force. Delivering 5,000 N of locking force, the HS1T is much more powerful than comparably-sized devices. This is achieved in such a compact size due to a metal head integrating the locking and mounting functions, an improvement over older designs, where the head could break away from the mounting body.

Also, to maximize installation options, the remaining actuator portion can be independently rotated from the high-strength head using only one screw. — *IDEC Corp., Sunnyvale, Calif.*
www.idec.com/usa

Genuine free-flow plate heat exchangers

The gasketed-plate heat exchangers of the NF series (photo) offer a free flow for all media. Unlike traditional models with herringbone corrugation, which have tapered flow channels, the channel cross-section of the NF series is always consistent. This allows particles to pass through more easily. The free-flow plate heat exchangers have a regular plate gap of up to 10 mm and a coarsely corrugated plate profile, ensuring a blockage-free operation with fibrous and solid media at high heat-transfer performance. The manufacturer's brazed-plate heat exchangers are used in the paper-and-pulp production process as highly efficient heat pumps, for example. They are characterized by a compact design and low investment and operating costs. — *Kelvion Germany GmbH, Bochum, Germany*
www.kelvion.com

These heavy-duty butterfly valves handle abrasives

The Series 585/586 inflatable seated butterfly valves (photo) are designed for the most severe of applications. The heavy-duty seat has been designed for higher operating pressures and temperatures. Standard valve sizes range from 2 to 24 in. (50–600 mm) and fit both ANSI and metric flanges. The valve is ideally suited for abrasive materials, such as sand, feldspar, flyash and most other dry, granular materials. The inflatable seat design provides a better seal by utilizing air pressure to expand the seat against the disc, providing more sealing area and an even pressure distribution against the disc every time. The seat automatically compensates for wear when it inflates against the disc, extending valve life considerably. The valves are available in a wide variety of construction materials, including stainless steel and aluminum. — *Posi-flate, St. Paul, Minn.*
www.posiflate.com

Gerald Ondrey

J. P. Sauer & Sohn Maschinenbau



IDEC



Kelvion Germany



Posi-flate

Liquid Mixing in Stirred Tanks

A method of quantifying mixing according to a mixing index is presented. This index can evaluate and predict mixing intensity related to fluid velocities in stirred tanks

David S. Dickey
MixTech, Inc.

The stirred tank is one of the most common and versatile pieces of chemical process equipment. While every chemical engineer has had a course about chemical reactors and has encountered the concept of a continuous stirred tank reactor (CSTR), very few of those same engineers can evaluate or predict the mixing performance of a stirred tank. While some stirred tanks are used as continuous flow reactors, others are used as batch reactors. Many more stirred tanks are used for physical processing of formulations without any chemical reactions. A method of quantifying mixing according to a mixing index can evaluate and predict mixing intensity related to fluid velocities in stirred tanks.

Various size stirred tanks are used to carry out an enormous variety of process objectives in nearly all of

the chemical process industries (CPI). While the processes can be very different, the underlying fluid dynamics are quite similar. A rotating impeller in a cylindrical tank causes fluid motion and liquid blending to promote the desired process results. The ability to quantify liquid motion in a stirred tank is a basic step toward understanding how mixing influences process results.

It is time to revive, update and extend the concept of a one-to-ten scale used to describe the fluid motion associated with mixing intensity.

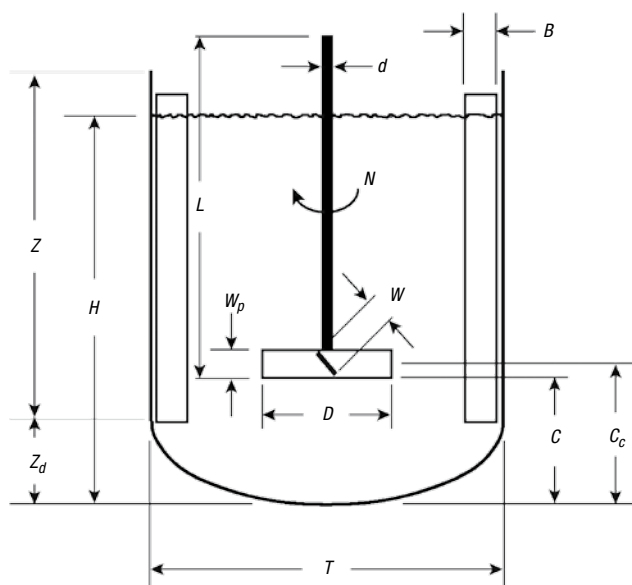


FIGURE 1. A basic stirred tank with its important parameters is shown here

The idea of a one-to-ten scale has two especially useful features to describe the often vague and otherwise imprecise measure of mixing intensity. These scale values will be called

NOMENCLATURE

B	baffle width, in.
D	impeller diameter, in.
E_p	pumping efficiency number
H	liquid level, in.
N	rotational speed, rpm
P	power, hp
Q	volumetric flow or pumping capacity, gal/min
T	tank diameter, in.
u	velocity, ft/min
V	volume, gal
W	impeller blade width, in.

Dimensionless groups and variables

$\{f_{\text{Index}}(N_{Re})\}$	viscosity correction factor for MI as function of Reynolds number
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$\{f_{\text{viscosity}}(N_{Re})\}$	viscosity correction factor for impeller power
MI	Mixing Index, 1 to 10 scale
N_{index}	Pumping Index, dimensionless pumping capacity for recirculation flow
N_p	power number
N_Q	pumping number
N_{Re}	Reynolds number

Greek symbols

ε	dissipation of kinetic energy per unit mass, m^2/s^3
η	Kolmogorov length, meters
μ	dynamic viscosity, centipoise
ν	kinematic viscosity, m^2/s
ρ	fluid density, sp.gr. (relative to water)
τ	time, min
φ	efficiency — kinetic energy divided by

mechanical energy

Subscripts

Axial	related to axial flow, pitched-blade or hydrofoil motion
eq	equivalent
Hydraulic	fluid motion effect
Hydrofoil	related to hydrofoil impellers
Mechanical	impeller motion effect
Pitched	related to pitched-blade turbines
Radial	related to radial flow, straight-blade motion
Straight	related to straight-blade turbines
Tip	impeller tip, peripheral motion
Turnover	turnover time, volume/pumping capacity



FIGURE 2. This pitched-blade turbine has four blades

Mixing Technology Group NOV



FIGURE 3. A typical three-blade hydrofoil impeller is shown here

mixing indices. First, the limits from one to ten describe the range of intensities commonly associated with industrial stirred-tank processes. A mixing index of one is considered to be the minimum level of liquid motion capable of moving all of the liquid in a stirred tank. A mixing index of ten is an upper limit to intensities encountered in most industrial process applications. Higher intensities and mixing index values are possible but less common. Second, the difference in intensity between consecutive mixing index values, such as the difference between an index of two and three, is about the limit of differentiation possible with any description of mixing intensity. The definition and calculation of the mixing index will further describe the meaning of this type of mixing intensity.

Most industrial stirred-tank problems, process improvements and product changes involve existing equipment. Often the existing mixers are more than twenty-five years old. Only a few chemical engineers will have an opportunity to specify a new stirred-tank mixer for their process. Many of those engineers who do get to select new equipment may rely on the knowledge and experience of an equipment manufacturer to get the right size mixer. Even with new equipment, the engineer may need to compare the designs offered by different suppliers. Being able to evaluate the mixing intensity of differ-

ent mixers is important at all stages of mixer design and use.

With an older, existing stirred-tank mixer, it was most likely designed for a different process, product or quality standard. Those differences mean that the mixer design may not be effective for the current situation. When process problems require solutions, new products must be produced, or production improvements are sought, different options need to

be considered and evaluated. The practicing engineer or scientist probably has little or no relevant background in liquid-mixing fundamentals and even less time to learn or investigate mixing when faced with a process problem or the production of a new product. Some basic concepts used by equipment manufacturers and mixing experts can be adapted for use by practicing engineers to evaluate and improve pro-



FIGURE 4. A typical straight-blade turbine is shown here

cesses involving liquid mixing. The performance or capabilities of the existing mixer should not be an unknown process characteristic.

Many different mixing variables for stirred tanks have been developed and reported over the years. These mixing variables are all based on empirical observation of the fluid motion, hydraulic forces and flow patterns of a mixer operating in a stirred tank. Even the computational methods rely on some connection between the modeled variables and observed process results. The typically observed quantities, such as power number, tip speed, power per volume, Reynolds number, torque, blend time, pumping capacity, discharge velocity, turnover time and hydraulic efficiency are all of limited utility to describe mixing intensity except when they are applied to either a similar impeller geometry or the same size process tank.

Background

Back in 1975 and 1976, *Chemical Engineering* published a CE Refresher series called Liquid Agitation [1–12]. Those mixer sizing procedures used a systematic, flowcharted method for sizing different general categories of applications based on the fluid phases present. The procedures also included the mechanical design of mixing equipment and some general scaleup and process categorizations on which to apply the procedures. Since the time of the original articles, mixing equipment and technology have evolved. While the fluid flow requirements are different for specific processes, such as solids suspension, emulsion formation, gas dispersion and viscous-liquid blending, a basic level of fluid motion is required for all types of processes.

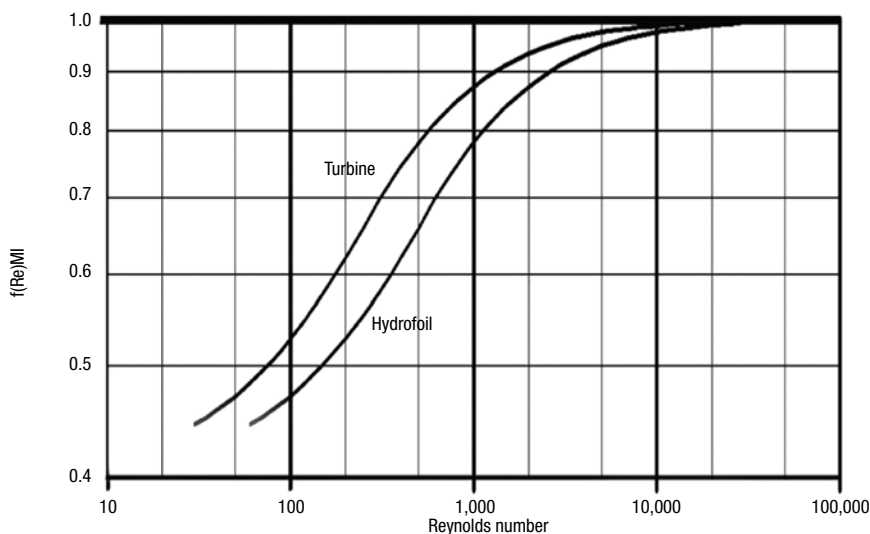


FIGURE 5. The mixing index correction factors for viscosity as a functions of Reynolds number are plotted here

This article and much of the mixing literature begin with the basic stirred tank, as shown in Figure 1. The primary length dimensions are impeller diameter, D , tank diameter, T , and liquid level, H , all of which are treated as inch dimensions for this article. Some length dimensions are often represented as ratios, such as D/T and H/T , to generalize the tank characteristics. The rotational speed, N , is typically reported in revolutions per minute. For effective turbulent mixing, baffles are needed to convert the rotational (tangential) flow created by the rotating impeller into the more effective axial or radial flow. Standard baffles are typically four vertical plates, mounted perpendicular to and near the tank wall at 90-deg intervals around the tank. The baffle width, B , is typically about one-twelfth the tank diameter. Rotational flow, without baffles, results in solid-body rotation of the liquid, which provides almost no mixing. The presence of a strong vortex on the surface is usually an indication of rotational flow and poor mixing, almost never successful mixing.

At the risk of stating the obvious, the required size and corresponding performance of any mixer depends on three basic factors: the quantity of fluid to be mixed; the difficulty of creating motion in the fluid; and the intensity or effectiveness of the fluid motion. The quantity of fluid can be measured by either volume or mass, but typically includes the density, which relates the volume to the mass. The difficulty of creating mo-

tion or mixing results depends on the process objectives and materials present. For liquid mixing, the fluid viscosity is an obvious difficulty parameter. The more viscous a fluid is, the more difficult it is to create and sustain motion in the fluid. Other categories of processes will have different difficulty parameters. The difficulty for solids suspension will be related to particle size, density and settling velocity. Gas dispersion difficulty will depend on at least the volumetric flow of gas and usually interfacial or viscosity effects. Even the difficulty of liquid blending may depend on additional factors, such as viscosity differences and interfacial tension.

No one factor will completely describe the effectiveness or intensity of liquid mixing, but making sure that fluid motion is present in all parts of a batch is essential. Higher velocities are likely to be more effective, within practical limits. The article in Ref. 4 provides a systematic way of defining a “bulk fluid velocity” or effective recirculating velocity. The bulk velocity is a function of impeller pumping capacity and tank cross-sectional area. The article describes the concept of a one-to-ten scale, which has been renamed in this article as a mixing index. The idea of a liquid mixing index is that most of the mixing effects associated in a stirred tank can be related to the liquid velocities in typical flow patterns. The “Pumping Number” in Figure 2 of the article [4] shows a strong function of the impeller to tank diameter ratio, D/T . More

recent studies typically find that the pumping number is a characteristic of the type of impeller, independent of D/T , and is often related to the impeller power number.

The literature on liquid mixing describes a pumping number or flow number in a few different ways [13], depending on the impeller type and flow pattern. A measured average velocity across the swept circular area of an axial discharge impeller or the cylindrical area around a radial discharge impeller can be used to define a discharge pumping number, N_Q . As soon as the flow leaves the discharge of an impeller, it begins to entrain surrounding fluid, increasing the effective volumetric pumping capacity. Depending on the impeller-to-tank diameter ratio, D/T , the entrained flow will recirculate and can be described by a circulating pumping number. The circulating pumping of an impeller is important for both the velocity and flow pattern in the tank. For example, the motion above a down-pumping, axial-flow impeller is a result of circulating flow.

The experimental and analytical methods for defining mixing properties often create empirical relationships that, while useful for basic analysis, often fail to include the effect of volume on mixer size or effectiveness. The impeller power number and pumping number are both commonly reported impeller characteristics. The dimensionless impeller power number, N_P , contains the obviously important mixer variables: power, P ; rotational speed, N ; impeller diameter, D ; and fluid density, ρ . To make the power number dimensionless using U.S. customary units requires a large conversion factor.

$$N_P = \frac{1.524 \times 10^{13} P}{\rho N^3 D^5} \quad (1)$$

The power number is effectively a constant for a given impeller geometry under turbulent conditions in a baffled tank. Impeller geometry factors, such as number of blades, blade width and blade angle, do affect the power number, but D/T has a relatively minor effect in most cases. No

amount of manipulation of the variables in the power number will tell you if a mixer will provide sufficient mixing or not, because the relationship is independent of tank size.

Even the obvious effect of viscosity on power is not reflected in the power number. Instead, the power number is typically correlated as a function of impeller Reynolds number, N_{Re} .

$$N_{Re} = \frac{10.7 D^2 N \rho}{\mu} \quad (2)$$

The conversion factor in the Reynolds number makes it dimensionless when using U.S. customary units with density, ρ , in specific gravity and viscosity, μ , in centipoise. Power number correlations can be found in a number of references, but some of the more relevant ones are in mixing handbooks such as Refs. 14 and 15.

The impeller Reynolds number is similar in concept to a pipe Reynolds number but has entirely different values. Turbulent conditions in a stirred tank exist for $N_{Re} > 20,000$.

Transition and laminar flow occur at lower Reynolds numbers — transition flow for $20,000 > N_{Re} > 10$, and laminar flow with $N_{Re} < 10$. The mixing index described in this article only applies to turbulent and transition conditions. Laminar mixing requires different impellers, typically with large diameters capable of physically moving the fluid in all parts of the tank. The Reynolds number is also not a measure of mixing intensity. It is only a representation of the type of flow created by the impeller. Turbulent flow has chaotic patterns while laminar flow follows streamlines. The inclusion of the impeller diameter squared in the Reynolds number means that larger tanks will have higher Reynolds numbers and more turbulent flow than in smaller tanks with the same velocities and fluid properties. Similar size effects exist with turbulent pipe flow.

The pumping number or flow number of an impeller is another possibly useful parameter for the description of mixing intensity. The pumping number, N_Q , is also dimensionless, making it independent of tank volume. The pumping capacity, Q , can be defined as discharge, entrained, or circulation pumping.

$$N_Q = \frac{231Q}{ND^3} \quad (3)$$

The impeller pumping capacity, Q , can be combined with the tank volume, V , to create a turnover time, $\tau_{Turnover}$.

$$\tau_{Turnover} = \frac{V}{Q} \quad (4)$$

If it were practical to predict an appropriate turnover time for a process requirement, the tank volume and pumping number could be used in finding an impeller diameter and rotational speed for effective mixing intensity. However, because the turnover time and blend time are closely related and always increase with the tank volume, an accurate prediction of appropriate times is difficult. A larger tank is expected to take longer to blend and the turnover time will also need to be longer. Estimating a turnover time or blend time is difficult without previous experience with the same process in a similar-size tank. Overestimating a turnover time or blend time sounds like it would be conservative. However, a longer time estimate will result in a lower pumping requirement, which means that either the speed or impeller diameter may not be large enough to move all the liquid in the tank.

Another variable often used to describe impeller performance is the impeller tip speed. Tip speed, u_{Tip} , is just the peripheral velocity of the impeller and can be computed from the rotational speed and the impeller diameter.

$$u_{Tip} = \frac{\pi DN}{12} \quad (5)$$

Tip speed is sometimes held constant when doing mixer scaleup, especially with geometric similarity. Constant tip speed means that for turbulent conditions, the other local velocities at corresponding geometric locations in the tank are also held constant. Equal tip speed scaleup works much like a constant mixing index. Be-

cause many laboratory-size containers and some pilot-scale tanks operate in the transition flow regime, scaleup at equal tip speed will also increase the Reynolds number. A higher Reynolds number will mean that the effect of viscosity will be less important at the larger scale. Therefore, equal tip speed may provide improved intensity because of the reduced effect of fluid resistance.

A variety of “flowrate efficiency” definitions can be found in other references [16]. For constant impeller diameter and speed, flowrate divided by power can be expressed as:

$$\frac{Q}{P} \propto \frac{N_Q}{N_P} \quad (6)$$

For the efficiency of same-size impellers at different speeds:

$$\frac{Q^3}{P} \propto \frac{N_Q^3}{N_P} \quad (7)$$

Impeller efficiency can be defined for any size and speed [17] assuming that neither N_Q nor N_P is a function of D/T .

$$E_P = \frac{Q^3 \rho}{PT^4} = \frac{N_Q^3}{N_P} \left(\frac{D}{T} \right)^4 \quad (8)$$

Other efficiency measures can be expressed as the kinetic energy of the fluid divided by the mechanical energy provided by the impeller [18]. The expressions for the kinetic to mechanical energy ratios differ for axial flow impellers and radial flow impellers, because of the different discharge areas.

$$\varphi_{Axial} = \frac{P_{Hydraulic}}{P_{Mechanical}} = \frac{8N_Q}{\pi^2 N_P} \quad (9)$$

$$\varphi_{Radial} = \frac{P_{Hydraulic}}{P_{Mechanical}} = \frac{N_Q}{2\pi^2 N_P} \left(\frac{D}{W} \right)^2 \quad (10)$$

The blade width, W , enters the expression for radial efficiency because the height of the cylindrical, radial discharge area is the blade width. These efficiency definitions are characteristics of the impeller geometry and are independent of the tank volume. Such efficiencies do not provide any insight into which impeller and operating condition will provide a successful process.

About the only commonly used mixing measure that provides a direct connection to some kinds of process results is power per volume or, more scientifically, power per mass. Local power per mass is an effective representation of kinetic energy dissipation. Energy dissipation can be directly connected to micro-scale turbulence by the Kolmogorov length scale.

$$\eta = \left(\frac{\nu^3}{\varepsilon} \right)^{1/4} \quad (11)$$

The Kolmogorov length scale is typically expressed in metric units, with the length scale, η , in meters, the kinematic viscosity, ν , in meters per second and the kinetic energy, ε , in meters squared per seconds cubed. The Kolmogorov length scale represents the smallest size of turbulent eddies. At sizes less than the Kolmogorov

length scale, the motion becomes chaotic molecular motion or heat. There are also Kolmogorov time and velocity scales with definitions based on the same variables.

The significance of micro-scale turbulence in stirred tanks is that such motion may directly affect the mixing rates for chemical reactants. In fast chemical reactions, especially ones with series/parallel paths and intermediate products, the product distribution and production efficiency of such reactions may depend on the local kinetic energy dissipation (power per mass). Because of the importance of fast chemical reactions in some processes, power per mass may be an essential variable that may be decided in pilot-plant studies or by previous experience with similar reactions. Of course, local energy dissipation is different at various locations in a stirred tank. Greater energy dissipation occurs near the impeller and lower dissipation near the surface. The mass in power per mass may be based on the swept volume defined by the impeller rotation or the total tank volume. Because of the comparable values of power per mass and power per volume in a constant density fluid, a modified mixing index to include power will be included later in connection with chemical reactions in a stirred tank.

One other practical measure of mixing intensity is torque per volume, which is much like power per volume, except that torque is more closely related to momentum transfer from the mixer to the fluid. On scaleup, equal tip speed for geometrically similar vessels is the same as equal torque per volume. Because of the similarity between torque per volume and fluid momentum, torque per volume can be a better measure to assure successful process results than power per volume in non-reactive, formulation processes.

Either power per volume or torque per volume depends on previous experience with similar applications. The values for successful power per volume or torque per volume are different and can be difficult to tabulate or remember. The idea of a mixing index provides a more convenient form of direct calculation and valuation. The appropriate magnitude of the index still depends on process

knowledge, but the one to ten scale provides both limits and increments to mixing intensity. Any measure of mixing is empirical and depends on observation of either physical or computational models. Correlations for power, blending and pumping all come from some type of empirical observations. The mixing index is just a convenient means of converting practical industrial experience into an empirical relationship.

Definition of mixing index

The mixing index, MI, begins where the definition of "Scale of Agitation" left off in Liquid Agitation [4]. The original article only applies to pitched-blade turbines. The following definitions and calculations will be expanded to include hydrofoil impellers and straight-blade turbines.

The typical pitched-blade turbine, shown in Figure 2, has four blades, mounted at a 45-deg angle to the horizontal with the actual blade width one-fifth of the impeller diameter.

A typical three-blade, narrow-blade hydrofoil impeller is shown in Figure 3. While different mixing equipment manufacturers make different hydrofoil impellers with different blade shapes, camber and widths, most companies offer an impeller with similar power number and pumping numbers for comparable performance.

A typical straight-blade turbine is shown in Figure 4. This straight-blade turbine has four blades, mounted vertically with blade widths one-fifth of the impeller diameter. The flow from this type of impeller is radial to the wall of a baffled tank with recirculation above and below the impeller.

As with most scientific and correlated mixing results, the effects of transitional flow conditions, different liquid levels, multiple impellers, and adjustments to impeller geometry are not provided in the reported results. By focusing on a practical definition of the mixing index and years of experience with the method for estimating mixing intensity, calculations can be reduced to simple formulas and correction factors.

This approach to the development of a mixing index could be considered as a layered process. The first step or layer is the development of basic formulas for the mixing index in turbulent conditions. For turbulent conditions, the pumping index (equivalent to the pumping number in the original article [4]) is a constant multiplied by a D/T function. To provide index calculations into the transition range, correction factors will be provided. The effects of liquid level will be handled directly using the actual tank volume, which creates an equivalent tank diameter to use in the mixing index calculation. Multiple impellers can be calculated separately and then combined by a formulation that produces reasonable results for most practical impeller spacings. Adjustments to the MI number could be made for impeller geometry modifications but are not addressed in this article.

The basic idea of a mixing index comes from the article by Hicks and others [4]. The assumption is that by using a "pumping number" that is a function of both D/T and Reynolds number, a "bulk fluid velocity" across an equivalent tank cross-sectional area can be calculated. The "bulk fluid velocity" is a representation of the recir-

culation pumping capacity. The practical aspect of the "bulk fluid velocity" in feet per minute is that it is equal to six times the mixing index. The factor of six is just an empirical factor that seems to work well for typical industrial mixing applications.

The equivalent tank diameter, Equation (12), is just the diameter for a cylindrical tank with the liquid level equal to the tank diameter, often called a "square batch."

$$T_{eq} = \left\{ \frac{4(231)}{\pi} \right\}^{1/3} (V)^{1/3} = 6.65(V)^{1/3} \quad (12)$$

The equivalent tank diameter is in inches and the volume is in gallons. To calculate the velocity across the area based on the equivalent diameter, a pumping index, comparable to a dimensionless pumping number times a D/T factor will be defined for each type of impeller. The turbulent pumping index numbers for the standard impellers are shown in Equation (13).

$$\text{Pitched-blade turbine: } N_{\text{Index}} = \frac{Q_{\text{Pitched}}}{ND^3} = 0.694 \left(\frac{0.394}{D/T} \right)^{1/2}$$

$$\text{Hydrofoil impeller: } N_{\text{Index}} = \frac{Q_{\text{Hydrofoil}}}{ND^3} = 0.418 \left(\frac{0.394}{D/T} \right)^{1/2}$$

$$\text{Straight-blade turbine: } N_{\text{Index}} = \frac{Q_{\text{Straight}}}{ND^3} = 0.929 \left(\frac{0.394}{D/T} \right)^{1/2} \quad (13)$$

The mixing index, MI, is the pumping rate, Q , for the impeller in cubic inches per minute divided by the cross-sectional area based on the equivalent tank diameter divided by six.

$$MI = \left\{ \frac{1}{(12)(6)} \right\} \left\{ \frac{Q}{(\pi/4)(T_{eq})^2} \right\} \quad (14)$$

The coefficient in the MI calculation converts inches per minute to feet per minute and makes the mixing index one sixth of the bulk velocity.

Multiplying the pumping index for each impeller times the rotational speed times the impeller diameter cubed and replacing the equivalent tank diameter with a cube root function of the tank volume forms the basis for the MI formulation. Rearranging the terms and pumping index numbers, coefficients can be found to calculate MI values for each impeller type. Since the functional relationships were developed for turbulent conditions with constant pumping index numbers, a fractional factor needs to be multiplied times the turbulent values to correct for the effect of viscosity. based on a Reynolds number correlation. The MI values for each impeller type are shown in Equation (15).

$$\begin{aligned} MI_{\text{Pitched}} &= 4.492 \cdot 10^{-4} \frac{N(D)^{5/2}}{(V)^{1/2}} \{f_{\text{IndexPitched}}(N_{\text{Re}})\} \\ MI_{\text{Hydrofoil}} &= 2.705 \cdot 10^{-4} \frac{N(D)^{5/2}}{(V)^{1/2}} \{f_{\text{IndexHydrofoil}}(N_{\text{Re}})\} \\ MI_{\text{Straight}} &= 6.013 \cdot 10^{-4} \frac{N(D)^{5/2}}{(V)^{1/2}} \{f_{\text{IndexStraight}}(N_{\text{Re}})\} \end{aligned} \quad (15)$$

For the purpose of evaluating an existing mixer application, the MI is a useful value. Rounded to one or at most two significant figures, the MI should indicate the expected mixing intensity. The utility of MI for evaluation can also be seen when the volume is reduced. A smaller batch volume should effectively increase the mixing intensity and may be an economical and safe way to test the effect of increased mixing intensity on a process. Changes to batch volume should have an effect equivalent to a somewhat larger mixer. If the increased intensity shows positive process results, other modifications to the mixer, such as a larger or different impeller, could be considered. As with all changes to a mixer, careful considerations need to be given to possible mechanical effects, such as motor overload or shaft critical speed problems.

The index correction factors as a function of Reynolds number are shown on the graph in Figure 5. The curve for turbines was developed for pitched-blade turbines, but can be a good approximation for straight-blade turbines. The curve for hydrofoils is indicative of the fact that the narrow, shallow angle blades become less effective than wider blades as the viscosity increases and the Reynolds number decreases.

Examples of expected intensities and process results [4] can be summarized as follows for mixing of the lower viscosity material in baffled tanks:

Mixing indices of 1 and 2 are characteristic of applications requiring minimum fluid velocities to achieve

the process result and are often applied in liquid storage applications.

Mixers capable of a $MI = 2$ will:

- Blend miscible fluids to uniformity if the specific-gravity differences are less than 0.1
- Blend miscible fluids to uniformity if the viscosity of the most viscous is less than 100 times the viscosity of the other fluid
- Establish complete fluid-batch control
- Produce a flat but moving fluid batch-surface

Mixing indices of 3 to 6 are characteristic of fluid velocities in most industrial mixed batches, especially those used to accomplish a physical process, such as formulations and heat transfer.

Mixers capable of a $MI = 6$ will:

- Blend miscible fluids to uniformity if specific-gravity differences are less than 0.5
- Blend miscible fluids to uniformity if the viscosity of the most viscous is less than 5,000 times the viscosity of the other fluid
- Suspend trace solids ($<0.2\%$) with settling rates from 2 to 4 ft/min
- Produce surface rippling at lower viscosities

Mixing indices of 7 to 10 are characteristic of applications requiring high fluid velocities for a rapid process result, such as a critical chemical reactor.

Mixers capable of a $MI = 10$ will:

- Blend miscible fluids to uniformity if specific-gravity differences are less than 1.0

- Blend miscible fluids to uniformity if the viscosity of the most viscous fluid is less than 50,000 times that of the other fluid
- Suspend trace solids (<0.2%) with settling rates of 4 to 6 ft/min
- Provide surging surfaces at low viscosities

Process results will vary, especially if the average viscosities put the Reynolds number in the transition range. Any time the viscosity is considered to be non-Newtonian, process applications become more difficult and the effective mixing index will be reduced. No mixing-index calculations should be taken as absolute results, but rather considered as approximations to typical industrial conditions.

For process improvement or modification situations, especially with a variable speed drive on the mixer, calculating the mixer speed needed to create a desired MI for an existing batch volume and impeller diameter may be more useful. The following calculations for mixer speed can be used:

$$\begin{aligned}
 N_{Pitched} &= 2,226 \frac{MI_{Pitched} V^{1/2}}{\{f_{IndexPitched}(N_{Re})\}(D)^{5/2}} \\
 N_{Hydrofoil} &= 3,696 \frac{MI_{Hydrofoil} V^{1/2}}{\{f_{IndexHydrofoil}(N_{Re})\}(D)^{5/2}} \\
 N_{Straight} &= 1,663 \frac{MI_{Straight} V^{1/2}}{\{f_{IndexStraight}(N_{Re})\}(D)^{5/2}}
 \end{aligned}
 \quad (16)$$

Changes in mixer speed should be made only with a review of the mechanical design. Lower speeds rarely cause problems, but increased speed may cause a motor overload or operation above the natural frequency of the shaft. Either type of mechanical problem could damage the mixer and even cause safety issues.

Notice that the fractional Reynolds number index correction is now in the denominator, meaning that to maintain the same mixing index the mixer speed must increase in the transition region. Also, in the transition flow range, the speed change may be enough to change the Reynolds number, which could change the index correction factor. In rare cases, more than one iteration to the adjustment mixer speed may be necessary. Mixer speed changes can be expensive with gear driven mixers. Although the speed change may seem possible, a larger gear reducer may be needed to handle the increased loads.

Because of the several potential mechanical and cost problems with a speed change, an impeller diameter or type change may be a better way to get process improvement. Most mixer drives operate at one of a few standard speeds. Starting with a standard speed of the existing speed, the mixing index can be used to calculate a potential impeller diameter.

$$\begin{aligned}
 D_{Pitched} &= 21.83 \frac{MI^{2/5} V^{1/5}}{\{f_{IndexStraight}(N_{Re})\}^{2/5} (N)^{2/5}} \\
 D_{Hydrofoil} &= 26.74 \frac{MI^{2/5} V^{1/5}}{\{f_{IndexHydrofoil}(N_{Re})\}^{2/5} (N)^{2/5}} \\
 D_{Straight} &= 19.43 \frac{MI^{2/5} V^{1/5}}{\{f_{IndexStraight}(N_{Re})\}^{2/5} (N)^{2/5}}
 \end{aligned}
 \quad (17)$$

These diameter calculations can also be used to look at diameters for other types of impellers by using the different MI calculations.

At this point, the mixing index has been defined for the single impeller in the “square-batch” tank. Many tanks do not have a liquid level equal to the tank diameter and many more batch tanks have variable liquid levels, such as while the batch is being created or as it is emptied. The MI calculations were developed using tank volume for a reason. Any stirred tank will have a liquid volume, but the same volume may not have the same liquid level in different tanks. Different MIs can be calculated for different levels in batch tanks. Changes to volumes in batch tanks can result in higher or lower MI values at different times in a batch process.

The liquid level is normally measured from the center of the bottom to the liquid surface. The shape of the tank bottom, such as flat, dished, elliptical, hemispherical or conical, will affect the liquid level even for the same volume. While bottom shape may have an observable effect on solids suspension, the effect on liquid motion is usually only minor and within the accuracy of the mixing index. In the extreme of a low liquid level, below the impeller, no mixing will take place. The amount of impeller coverage for satisfactory mixing depends on several factors, including impeller diameter, rotational speed and fluid properties. As a general guide, the impeller needs to be covered with liquid to about half an impeller diameter above the top of the impeller to avoid excessive splashing.

At the point where the liquid level is significantly greater than the tank diameter, multiple impellers may be needed to adequately control liquid motion in the entire batch. “Significantly” will depend on the fluid viscosity and impeller location, but the distance from the top of the impeller to the liquid surface is especially important. Too much surface motion and splashing may cause air incorporation or foaming. Too little surface motion may cause problems with ingredient addition, even liquids, but especially with the addition of solids.

Multiple impellers are an obvious and common solution to handling liquid levels, especially those greater than the tank diameter. The question then becomes, how should the MI be calculated for multiple impellers. Rigorous calculations by impeller control zones are more complicated than the accuracy of the MI justifies. A simple, but adequate calculation for the total MI can be done with separate calculations for each impeller, using the actual

impeller diameter, rotational speed and the total tank volume. Obviously, using the total volume with each impeller neglects the benefits of the other impellers. Taking a sum of each individual impeller's MI squared and then the square root of the total gives a good estimate for the total MI_{Total} .

$$MI_{Total} = (MI_1^2 + MI_2^2 + \dots MI_n^2)^{1/2} \quad (18)$$

The MI_{Total} becomes more accurate the more similar the impellers are in size and type and the more evenly spaced they are. Stirred tanks rarely have more than three impellers, so the square root of the sum of squares is usually an easy calculation. The whole concept of the mixing index provides a convenient and consistent measure of mixing intensity without extensive research or analysis.

Evaluating mixer power

The entire development of the mixing index has focused on the ability of the mixer to pump and recirculate liquid. All of that fluid motion requires an application of rotational force by the impeller blades on the fluid. The power provided by the mixer drive creates the force that rotates the impeller and moves the fluid. The power applied to the fluid also results in turbulent energy dissipation. All the turbulence in the liquid motion eventually degrades to molecular motion or heat. All mixers are 100% power efficient in converting impeller power into heat. However, that energy dissipation also creates the micro-scale turbulence that may help bring chemical reactants together quickly enough to produce desired reaction products.

Being able to predict the amount of power transferred from the mixer to the fluid has important potential benefits for chemical reactions, but is also essential for mechanical design of the mixer. The impeller power helps define the requirements for a motor. The motor speed and speed reduction establish the torque requirements for the strength of the drive, shaft and impeller blades. Once the impeller diameter, type and rotational speed are decided

by any means, the turbulent power can be calculated from a rearrangement of the power number.

$$P = \frac{N_p \rho N^3 D^5}{1.524 \times 10^{13}} \quad (19)$$

The turbulent power number, N_p , for the common impeller types mentioned earlier are as follows:

$$\text{Pitched-blade turbine: } N_{p\text{Pitched}} = 1.37$$

$$\text{Hydrofoil impeller: } N_{p\text{Hydrofoil}} = 0.3$$

$$\text{Straight-blade turbine: } N_{p\text{Straight}} = 3.96 \quad (20)$$

In the transition region, as the fluid viscosity increases, the impeller power will also increase. As with the

MI, the turbulent power can be multiplied by a correction factor to describe power requirements in the transition range:

$$P = \frac{N_p \rho N^3 D^5}{1.524 \times 10^{13}} \{f_{\text{viscosity}}(N_{\text{Re}})\} \quad (21)$$

A graph of the correction factors as a function of Reynolds number is shown in Figure 6.

If the impeller power is used for motor sizing, the motor should have a 15% greater power rating than the calculated impeller power. Although constant under turbulent conditions, actual impeller power can vary with respect to extreme factors, such as large D/T and close off-bottom clearance, C/D . Large D/T , greater than 0.5, and/or C/D , less than 0.5, can increase power requirements for some impellers.

The power requirements for a mixer with multiple impellers can be obtained by simply calculating the impeller power for each impeller and then adding the individual power values together. If some of the impellers are separated by less than half an impeller diameter, the actual power may be a little less than the sum of power values. When using power for mechanical design, the motor power should be used, because process changes or other factors may ultimately be able to apply the full motor power to the mixing equipment.

If power is important to the process variables, as when small-scale turbulence influences chemical reactions, then impeller power is important. As a rough guide to local energy dissipation, about half of the impeller power is dissipated in the volume around the impeller and the remaining is spread throughout the tank. As a further note about fast reactions, simple reactions such as acid-base neutralization happen so fast and irreversibly that almost any amount of turbulence is enough to make them happen. Blend-time measurements often use acid-base reactions with a color-change indicator to observe the location of the final color removal for a measure of mixing uniformity. The blend time is closely related to the tank turnover time, which is driven by impeller pumping and tank volume. The blend time is primarily a function of the time required to circulate the reactants and to avoid locations of weak motion. Many types of blending processes can be evaluated by the mixing index.

The chemical reactions most likely to be influenced by small-scale turbulence are combinations of series and parallel reactions with multiple kinetic steps, each with different reaction rates. In such reactions, impeller power and local energy dissipation can be important. Because impeller power, power per volume, or power per mass can be important, including at least the impeller power in a form of evaluation for the mixing index may have advantages in some situations. An estimate of process power for an application can come from a variety of sources, such as pilot plant testing, previous process experience, or literature references. If the process requirement is in the form of power per mass or power per volume, the tank volume, which is also

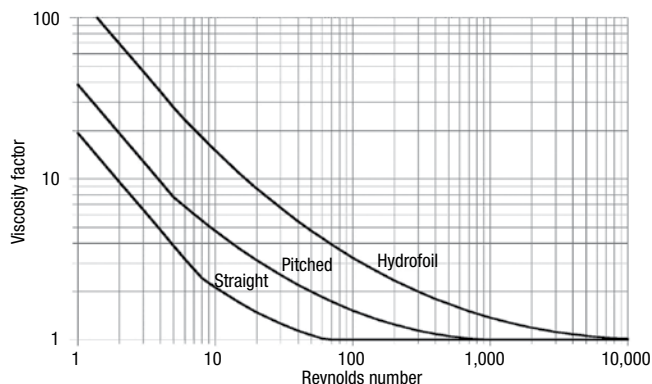


FIGURE 6. This graph shows the viscosity correction factors for impeller power as a function of Reynolds number

needed in the MI calculation, can be used to calculate an impeller power value. Whatever value is available for design or evaluation, the impeller power can be derived as a process requirement. For any given impeller type, various combinations of impeller diameter and speed will establish an impeller power. For the same MI, higher power inputs can be achieved at smaller D/T s. Calculations for a mixing index can be developed from impeller power, D/T , liquid density and batch volume by the following formulas:

$$\begin{aligned} MI_{\text{Pitched}} &= 48.63 \frac{P_{\text{Pitched}}^{1/3} (D/T)^{5/6}}{\rho^{1/3} V^{2/9}} \\ MI_{\text{Hydrofoil}} &= 48.59 \frac{P_{\text{Hydrofoil}}^{1/3} (D/T)^{5/6}}{\rho^{1/3} V^{2/9}} \\ MI_{\text{Straight}} &= 45.70 \frac{P_{\text{Straight}}^{1/3} (D/T)^{5/6}}{\rho^{1/3} V^{2/9}} \end{aligned} \quad (22)$$

These calculations are only for turbulent conditions. Calculations in the transition region involve correction factors for both the power and the index. Those formulations are possible, but more complicated than usually needed. Of interest, both the pitched-blade turbine and hydrofoil impeller have the same MI for the same power and D/T .

Those same formulas can be rearranged to calculate a power requirement for MI and the other parameters:

$$\begin{aligned} P_{\text{Pitched}} &= (8.700 \times 10^{-6}) \left\{ \frac{\rho (MI_{\text{Pitched}})^3 V^{2/3}}{(D/T)^{5/2}} \right\} \\ P_{\text{Hydrofoil}} &= (8.700 \times 10^{-6}) \left\{ \frac{\rho (MI_{\text{Hydrofoil}})^3 V^{2/3}}{(D/T)^{5/2}} \right\} \\ P_{\text{Straight}} &= (1.050 \times 10^{-5}) \left\{ \frac{\rho (MI_{\text{Straight}})^3 V^{2/3}}{(D/T)^{5/2}} \right\} \end{aligned} \quad (23)$$

Instead of power, the formulas can also be rearranged for power per volume or power per mass as desired.

Final remarks

The mixing index provides a simple measure of mixing intensity for many different kinds of stirred tank applica-

tions and processes. The index is not intended to be a test for subtle differences between mixing situations, but rather a simple way of evaluating or designing mixers for stirred tanks. Many applications require a means for process comparisons, improvements, or alternatives. ■

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Beyond Simple Mixing

Five different examples are presented in which specialty mixers are used to perform tasks more efficiently than conventional approaches

Christine Banaszek
Charles Ross & Son Co.

IN BRIEF

FINE EMULSIFICATION

MEDIA MILLING

REACTIONS

WET GRANULATION

DRYING

Specialty mixers serve a vast range of applications throughout the chemical process industries (CPI). The approach to mixer selection invariably starts with examining the different phases to be combined (solid/liquid, liquid/liquid, semi-solid/liquid, gas/liquid and so on). Considering the miscibility of the various raw materials, it's easy to see how the underlying objective — uniformity — is easier to achieve in some mixing operations more than others. Apart from miscibility, various other application factors impose challenges to mixing. These include non-Newtonian behavior, agglomeration, sensitivity to shear, temperature-related degradation and competing chemical reactions, just to name a few.

Uniformity is intrinsically a necessary condition in many unit operations such that specialty mixers frequently take on challenges well beyond mixing per se. For the purpose of this article, specialty mixers are those classes of mixing equipment capable of more than simple agitation of miscible low-viscosity liquids. Off-the-shelf propellers, turbines and similar low-speed agitators are thus excluded. This article will not discuss all types of specialty mixers, but cover five processing challenges wherein well-designed mixers may strategically replace traditionally accepted technologies and reap substantial benefits including improved efficiency and lower production cost.

Fine emulsification

In past decades, manufacturers of very fine emulsions have been forced to build their



FIGURE 1. This patented in-line ultra-high shear with 9-in.-dia. rotor/stator is capable of pumping up to 90 gal/min (based on water viscosity)

operations around expensive high-pressure homogenizers. Aside from high capital cost, other drawbacks of these homogenizers included low throughput, frequent clogging, labor-intensive cleaning and high maintenance. High-pressure homogenizers force fluids through a narrow gap where the resulting high pressure is converted into shear stress. Typical pressures range from 20,000 to 60,000 psi or higher. These conditions are useful for forming very fine emulsion droplets, reducing particles or agglomerates and rupturing cell membranes.

Today, a new generation of “ultra-high shear” rotor/stator mixers exhibit the capability for delivering intense emulsification with rugged efficiency. For example, a patented mixer (U.S. Patent No. 5,632,596) turns at tip speeds over 11,000 ft/min, and the rotor consists of concentric rows of intermeshing teeth (Figure 1). Product enters from the center of the stator and moves outward through radial channels in the rotor/stator teeth.

The combination of high tip speed and extremely close tolerances between the interlocking channels subjects the product to intense shear in every pass. The gap be-



FIGURE 2. This mixer is suitable for use with multiple interchangeable vessels that may be dedicated to specific product recipes or color formulations to further simplify cleaning and minimize cross-contamination

tween adjacent surfaces of the rotor and stator is adjustable for fine-tuning shear levels and flowrates. Sample applications include adhesives; cosmetics and personal care products (creams, lotions, sunscreen, soaps, deodorant, hair products, and so on); flavor emulsions, condiments, salad dressing, sauces and spreads; gum dispersions; greases and lubricants; latex emulsions; nanoparticle dispersions and composites; petroleum and biodiesel applications; pharmaceutical emulsions and suspensions; electronic inks and battery slurries; specialty coatings and chemicals.

Users of high-pressure homogenizers may consider testing an inline ultra-high shear mixer to produce fine emulsions. The value of actual testing cannot be overstated because in any emulsification process, the resulting droplet-size distribution is very much formulation-dependent.

Where an ultra-high shear mixer successfully replaced a high-pressure homogenizer, major benefits included lower production cost, simpler maintenance, easier cleaning and increased throughput. Although these machines can break down solid agglomerates, they are not appropriate for primary particle size reduction, cell disruption or milk fat homogenization.

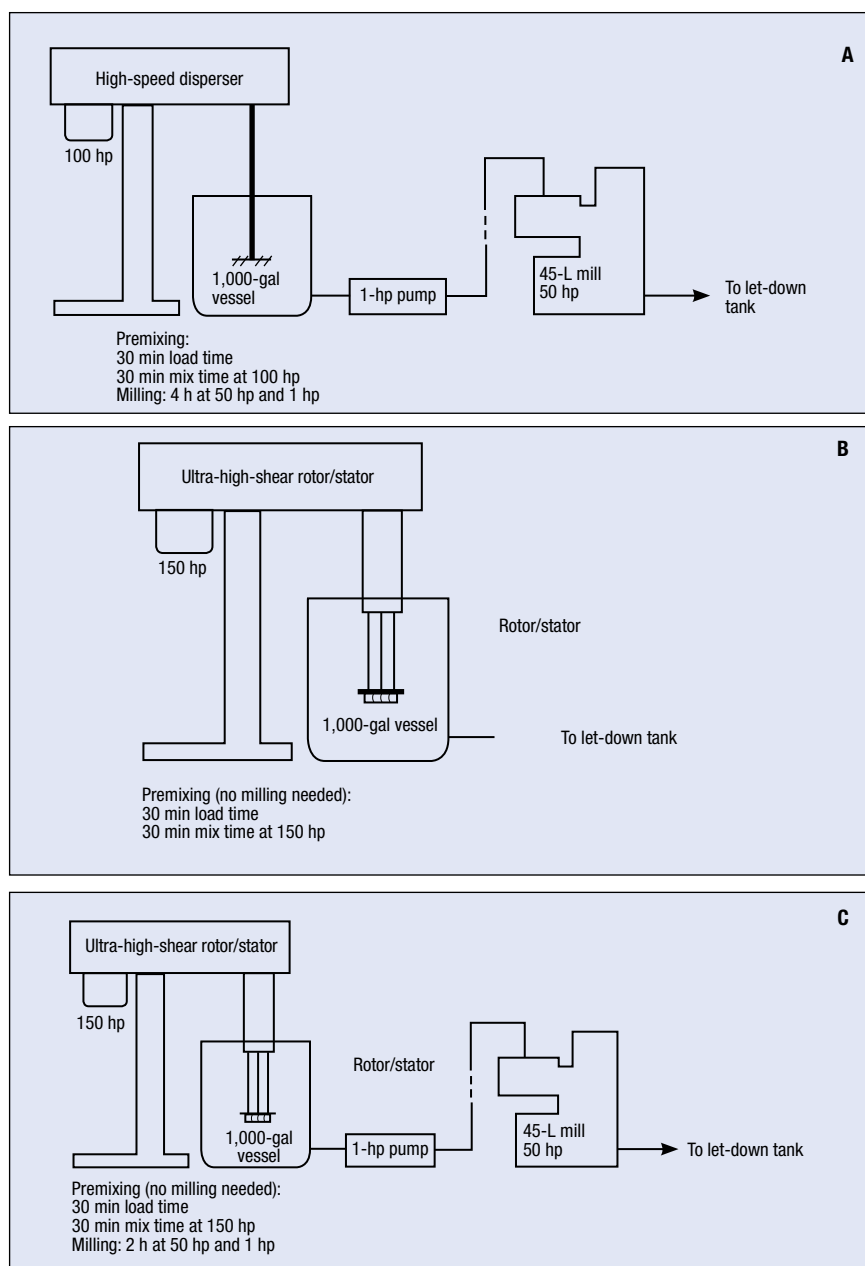


FIGURE 3. A media mill used in conventional processes (A) may be eliminated altogether — with significant reductions in energy consumption — using an ultra-high-shear rotor/stator (B). In some cases, the ultra-high-shear mixer will not completely replace the media mill, but reduce the number of mill passes required (C)

Media milling

Media mills are traditionally used for pigment dispersions in the paint, ink and coating industries. Media milling is often the process bottleneck and poses difficulties in terms of cleaning. Depending on the formulation, a batch-style ultra-high-shear mixer may produce results comparable to one or two passes through a media mill. The main advantage this offers is the ability to combine raw materials and bring the batch to its final dispersion quality in a single vessel. Such “one-pot” processing elimi-

nates transfer steps and simplifies cleanup, dramatically cutting overall cycle time while reducing costs.

One example of a batch design ultra-high-shear mixer is the patented (U.S. Patent No. 6,000,840) device shown in Figure 2. This ultra-high-shear mixer is capable of tip speeds up to 5,000 ft/min, which is approximately 25–60% faster than conventional rotor/stators. Precisely contoured for high pumping capacity, the mixer generates a double vortex (top and bottom of the mixing head) and easily



FIGURE 4. This dual-shaft mixer features Teflon-coated wetted surfaces and PEEK (polyetheretherketone) disperser blade designed for a reaction/mixing application that cannot contact stainless steel

handles viscous dispersions up to 50,000 cP.

Alternative scenarios. Figure 3 shows three different scenarios for media milling. A typical conventional configuration is shown in Figure 3A, consisting of a high-speed disperser, a pump that moves material to the mill and controls recirculation, the mill itself and a let-down tank in which the viscosity of the mix is adjusted. A total processing time of 5 h or more, from premixing through milling, is not uncommon with such a setup. The total energy consumption in the scenario in Figure 3A is 189.5 kWh.

By using a high-flow, ultra-high-shear rotor/stator, one manufacturer has been able to shift to the scenario in Figure 3B, eliminating the disperser, auxiliary pump and 45-L mill. Total batch time was reduced to 60 min — a reduction of 80%. Waste generation and cleaning were significantly diminished in the streamlined operation. Clean-up required by the ultra-high-shear mixer is identical to the disperser. The total energy consumption decreased by 70% to 55.9 kWh.

For some dispersions, the media mill cannot be entirely replaced by an ultra-high-shear mixer. But the milling cycle can be cut sharply, which still produces an overall increase



FIGURE 5. A 15-gal double planetary mixer designed with a slight tilt for easy and complete discharge of dried granulations

throughput and reduction in energy consumption as detailed in the scenario in Figure 3C. Total batch time for this modified process is 3 h, a 40% reduction from Scenario A, and the total energy consumption dropped by 30%, to 132 kWh.

Reactions

In almost any reaction process, it is safe to assume that mixing efficiency greatly influences yield, purity and quality. Conventional batch reactors employ a low-speed impeller or anchor agitator for continuous stirring of the reactants. Because initial development work is often carried out in generic laboratory glass reactors designed to accommodate a wide range of common multi-phase reactions, many pilot and full production processes are scaled up to resemble the laboratory configuration. This, however, poses problems when the product undergoes viscosity spikes or other drastic changes in rheology, the effects of which become more pronounced as batch size goes up.

Multi-shaft specialty mixers are ideal for applications up to several hundred thousand centipoise. For example, polymerization reactions can be conveniently accomplished in a triple-shaft mixer, wherein one of the independently driven agitators

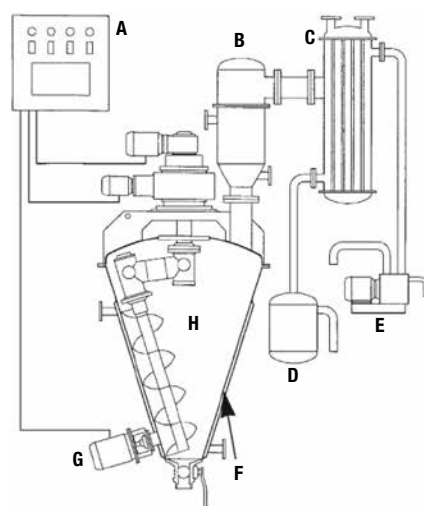


FIGURE 6. Vacuum drying in a vertical blender can save considerable time over conventional tray dryers. In this diagram, the control system (A) monitors and controls all process variables. The filter (B) excludes powders from the piping system. The condenser (C) chills vapor to a liquid state for the receiver (D). Other items are the vacuum pump (E), Jacketed vessel (F), high-speed lump breaker (G) and vertical blender/dryer with orbiting auger screw (H)

is a three-wing anchor with scraping blades that promote superior heat transfer across the jacketed vessel sidewalls and bottom. The two other agitators could be a high-speed disperser blade and a rotor/stator mixing head, both of which promote rapid powder wet-out, deagglomeration, dissolution and homogenization. Special design rotor/stators are even capable of sub-surface induction of hard-to-disperse or lightweight powders. Designs are available that generate an intense vacuum, which draws solids right into the high-shear zone of the mix chamber. This method of addition prevents hydrophobic powders from floating on the batch surface or forming lumps and “fish eyes.” To minimize dusting, the operator can use a “hose and wand” attachment and simply draw powders straight from the bulk container.

Real-world example. A 10-gal dual-shaft mixer serves as a reactor in a production line for conductive pastes and slurries. The finished products are tailored for use in various printed electronics, from computer monitors, TV screens and phone displays, to smart tags and solar cells.

The vacuum-rated mixer is equipped with a two-wing anchor

and high-speed disperser. A recirculation line is piped to the mix vessel, equipped with a centrifugal pump and inline filter. A built-in vacuum pump and mixer controls are also supplied as part of the turnkey reactor package.

The dual-shaft mixer replaced an old, low-throughout process that required several transfer steps. In the previous process, the base liquid and polymer were combined in a glass reactor and agitated with a propeller for over 15 h. Upon completion of the reaction, signaled by a smooth lump-free mixture, the reacted material was then passed through a filter and degassed in a separate machine. The dual-shaft mixer not only combined the mixing, dispersion, reaction, deaeration and filtration steps in a single vessel, it also dramatically reduced overall cycle time to less than 2 h. The ability to pull vacuum on the batch during mixing provides the additional advantage of enhancing dispersion quality.

Wet granulation

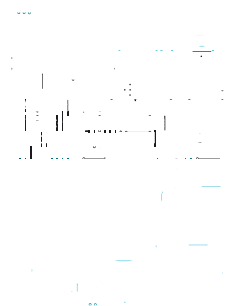
In the pharmaceutical and food-supplement industries, granulation is a very common unit operation that transforms fine powders into free-flowing, dust-free granules of a particular size and that are easy to compress.

High-speed granulators are used to first combine the various dry powders, and to this blend a binding fluid is added which transforms the batch into a wet mass. The chopper blade in the granulator breaks up the mass of material into smaller granules. Blade design and speed both affect granule size and uniformity. In certain tablet production processes, the resulting wet material is transferred to a drying step, then passed through an oscillating sieve mill to produce granules of a chosen size. Disintegrants and lubricants may be added in the final mixing step.

Alternatives to traditional granulators that are worth investigating include change-can planetary mix-

ers (Figure 5) that have been shown to be capable of carrying out all phases of a typical wet-granulation procedure, including blending, wet massing, drying and milling. An example configuration is a planetary blade working in tandem with a high-speed chopper. Both agitators turn independently on their own axis while revolving around the mix vessel. "One-pot" granulation may also be achieved in a double planetary mixer equipped with two identical blades. This latter design applies to applications that do not require any fast chopping or dispersion motion.

As granulation techniques and technologies continue to develop and improve, it has become even more valuable to perform actual testing, because end-product quality is entirely dependent on the complex interplay between the processing method itself and the myriad of physical and chemical characteristics of a particular formulation and its raw materials.



Drying

It is not unusual for tray-drying operations to run for many hours, sometimes overnight, in order to reach very low moisture levels. Vacuum ovens and tray dryers offer better drying rates than their atmospheric counterparts. Due to the reduced pressure within the dryer, the liquid's boiling point is lower than at atmospheric conditions and drying can proceed at lower temperatures. Vacuum drying is therefore ideal for processing heat-sensitive materials without risk of thermal degradation. It also allows manufacturers to recover costly solvents or safely dispose of any harmful volatile compounds removed from the closed system.

In addition to vacuum, agitation further improves a drying operation. A vertical blender/dryer (Figure 6), for instance, gently blends the product so that materials in direct contact with the vessel's heated surfaces are continuously renewed. Drying is not only fast but also uniform. This type of blender/dryer features a slow-

turning auger screw which orbits around a conical vessel. The screw lifts material upward as it advances along the vessel walls. At the same time, materials at the upper most level of the batch cascade slowly back down into regions opposite the moving auger screw. The constant exchange of materials between the heated sidewalls and center of the blender accelerates the drying process. A main issue with agitated dryers is the risk of product attrition or generation of fines. This concern is well minimized on a vertical blender/dryer. The blending action it imparts is very thorough but gentle enough even for the most delicate of applications. Another advantage of a vertical blender/dryer is the wide range of feed forms that they can accommodate — from slurries, wet cakes and pastes, to granules, pellets and powders. A liquid feed material, for example, may undergo a series of relatively swift changes in physical state — from slurry to a viscous paste, and from a paste to a dry powder.

It's worth noting that because the vertical blender facilitates precise vacuum control, uniform temperature and solvent recovery, it can also be utilized for extraction processes.

Another type of mixer employed for drying is the tumble blender, which also offers very gentle and low-impact mixing inside a V-shaped or double-cone rotating vessel. It is highly recommended for high-density applications. Other designs include planetary mixers as well as horizontal blender/dryers equipped with ribbon or paddle agitators. ■

Edited by Gerald Ondrey

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Considerations for Industrial Gas Purification

Purity requirements and gas properties require different methods for the purification of industrial gases. Provided here are key considerations for selecting gas purification technology

Brian Warrick and Dan Spohn

Applied Energy Systems Inc.

Industrial gases are critical for a wide range of applications throughout the chemical process industries (CPI). In most cases, industrial gases are produced to a particular purity specification, which means they may contain only a limited quantity of contaminants. For many applications, the gases provided by suppliers may not meet process specifications for a given process, meaning that the gas would require purification to further reduce contaminants. An improved understanding of industrial gas generation, storage and separation can help with the selection of the gas purification technology that meets process needs. A number of key considerations can have an impact on the type of gas purifier selected. These include the following: the production method for the gas supply; the purity of the gas source; how the gas source is packaged; the species of impurity molecules to be removed and the expected purity; as well as media selection, media capacity, space velocity, package design and shipping requirements. This article discusses the production of industrial gases with respect to methods of purification, storage, safety and shipping.

Many methods of gas generation exist, but for this article, we will mostly consider the physical separation of components (such as nitrogen from air or hydrogen from natural gas), rather than generation of gases via chemical reactions. Reactions gener-

ate gases such as ammonia, using the Haber-Bosch process. Other reactions create gases such as NO, SiH₄, PH₃, and so on, which are commonly used in the electronics industry.

Physical gas separation

Physical gas separation relies on membrane, catalytic and adsorption processes, cryogenic distillation, and other technologies. A few common ones are discussed here.

Membrane separation. A common air-separation technology uses hollow fiber membranes to separate nitrogen from oxygen (Figure 1). Membrane technology is commonly used when purity requirements are not stringent. Within the membrane system, many thousand hollow fibers are placed in a housing and compressed air is supplied to one end. The fiber wall is permeable to gases, but the diffusion rate across the fiber wall varies by gas. For air, oxygen, carbon dioxide, argon, and other trace contaminants pass through the wall a faster rate than nitrogen, and are directed to vent. Nitrogen exits the membrane system at a typical purity of greater than 95%. The purity achieved by a membrane-based system can be varied by the user by adjusting the flow through the system. The advantage of a membrane-based system is there are no moving parts, but outlet

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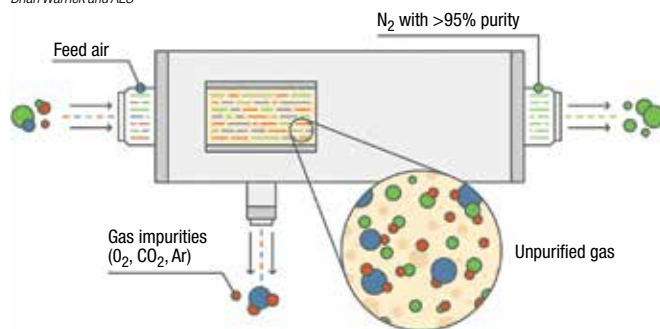


FIGURE 1. Membrane separation devices, used when purity requirements are not stringent, employ hollow-fiber membranes to separate nitrogen from oxygen

purity may vary with flowrate.

Pressure-swing adsorption. Pressure swing adsorption (PSA) and vacuum pressure swing adsorption (VPSA) are used where purity requirements are higher. When separation of impurities in the high parts-per-million (PPM) level is required, as opposed to separation of impurities at the percentage level, PSA is an option (Figure 2). PSA systems are typically used as pre-purification of gases entering a cryogenic process and for the purification of hydrogen. VPSA technology (Figure 3) is used for on-site float glass production and medical-grade oxygen.

PSA systems consist of pairs of vessels operating in parallel, or they can be designed in configurations with multiple vessels in series. Each vessel is packed with adsorption media, such as carbon molecular sieves, zeolites and charcoal. Feed gas to be purified passes through one or more vessels operating at pressures typically greater than 100 psig. Impurities within the feed gas stream are physically adsorbed (physisorption) onto the surface of

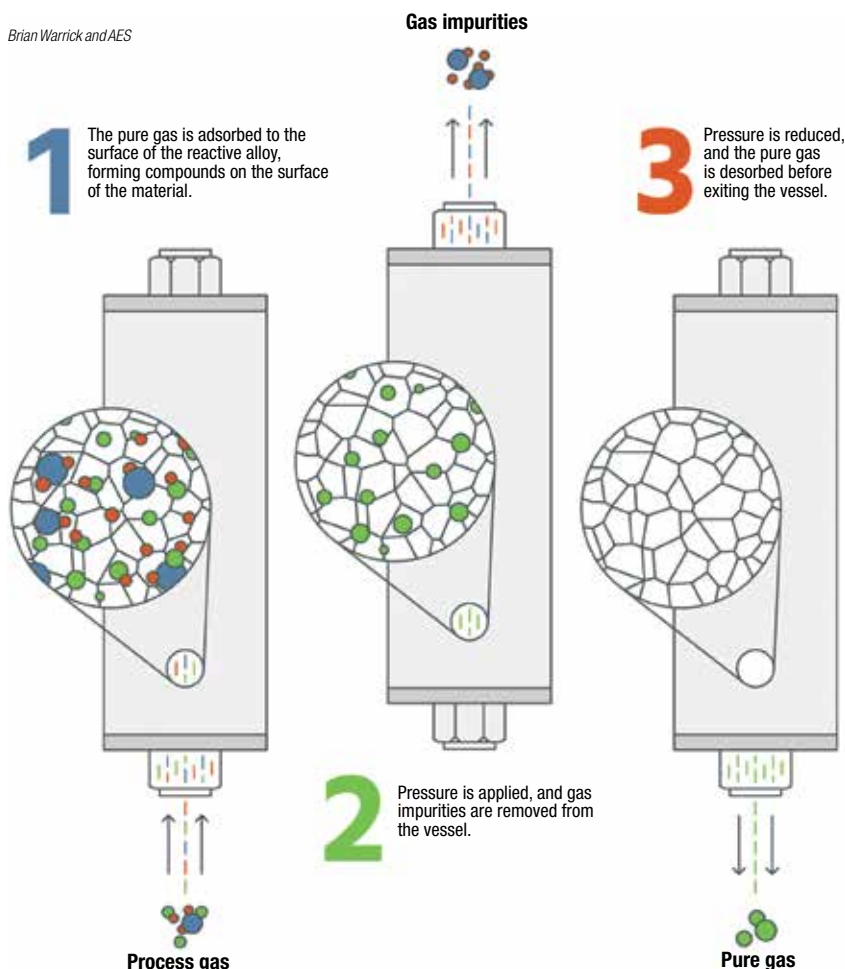


FIGURE 2. Gases can be purified using a range of different purification media, including zeolites, metal alloys and others

the media by Van der Waals forces (weak bonds created by short-range electrostatic interactions among molecular dipoles). PSA systems work by taking advantage of differing adsorption behavior at different pressures and temperatures. Adsorption sites are occupied by impurity molecules, while the desired gas passes through the media. Capacity for each impurity varies based on the media selection, often determined by the pore size. As impurity molecules break through the PSA vessels, the media requires regeneration to remove the adsorbed impurities. Within a PSA system, the vessel is isolated and the gas is rapidly vented to atmospheric pressure, which releases the trapped impurities. The vessel is then repressurized and is ready for more feed gas. This regeneration may be completed at a cycle time of minutes to hours. For the separation of nitrogen or oxygen from air, the cycle is typically short.

Cryogenic distillation. When low-

parts-per-million-level gas purity is required, cryogenic distillation is typically used. Cryogenic processes are based on the physical separation of gases relative to boiling point. Many gases may be cryogenically separated, but air separation is described here (Figure 4). Compressed air is chilled and then passes through a molecular sieve bed to remove moisture, hydrocarbons and carbon dioxide before entering the distillation column. Gas entering the column is cooled to cryogenic temperatures against outflowing gases. To maintain the balance of refrigeration needed to sustain the process an expansion turbine is often used. The air travels up the column through a series of trays against reflux liquid that is cascading down the column. Separation of the gases occurs because of different boiling temperatures. Nitrogen at 99.999% pure or greater may be supplied directly as vapor, or liquified for cryogenic delivery. Impurities within the nitrogen typically include carbon

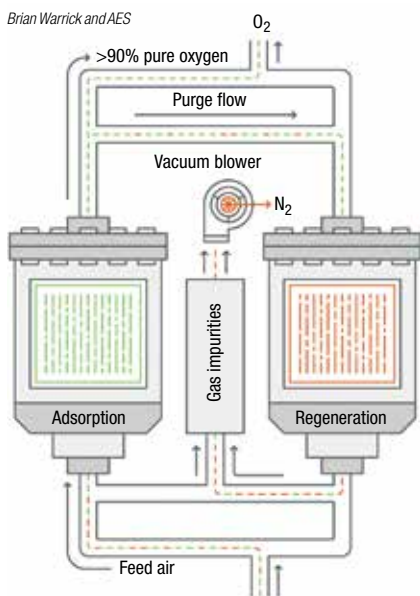


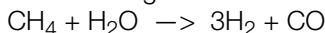
FIGURE 3. Vacuum pressure-swing adsorption is used when gas purity requirements are higher

monoxide and hydrogen, which have a similar or lower boiling point.

H₂ and He generation

Some gases are generated from stored reserves, such as natural gas. Helium is recovered from select gas fields, throughout the southwestern U.S. and other select areas of the world. Recovered helium may be liquefied for use in magnetic resonance imaging (MRI; the largest consumer of helium), as well as device cooling within the electronics industry, for flotation devices and others.

Hydrogen is produced from natural gas using a steam methane reformer (SMR) and is the source of more than 90% of all hydrogen. With a SMR, steam and methane from natural gas react over a catalytic material at elevated temperature to create hydrogen and carbon monoxide according to the following reaction:



The H₂- and CO-rich stream further reacts with another catalyst to generate hydrogen and carbon dioxide. This hydrogen then enters a PSA system, in which carbon dioxide is separated, while trace levels of contaminants are trapped at elevated temperature and then released during the depressurization step. Hydrogen may be liquefied for delivery into a cryogenic storage tank or supplied as a vapor via tube trailers, cylinders or pipeline. Cryo-

genic hydrogen will typically meet a purity level of 99.99999% without further purification.

Gas storage

Once generated, industrial gases are typically stored for delivery in cylinders, tube trailers, liquid containers, or connected to a pipeline after on-site generation. Storage cylinders range in size from small volume, and sub-atmospheric delivery pressure to greater than 200°C at pressures exceeding 3,000 psi. Tube trailers contain multiple horizontal tanks operating at high pressure and capable of storing thousands of cubic feet of gas. Hydrogen and helium are commonly stored in tube trailers. Atmospheric products, such as nitrogen, argon and oxygen, as well as specialty products, such as ammonia, are stored in dewars as a liquid or cryogenic product. Dewars are typically on wheeled bases, which allow for easy transport. During use, liquid is vaporized at a typical pressure greater than 100 psi. Dewars are commonly used for orbital welding, where a gas purge is required to protect the weld from contamination.

For production facilities requiring large quantities of gas, bulk liquid storage or on-site generation is common. On-site storage of cryogenic nitrogen, oxygen and argon (commonly referred to as bulk atmospheric gases; BAG), as well as hydrogen, ammonia, and others, allows for uninterrupted flow and stable delivery pressure. BAG and hydrogen products are stored in insulated horizontal or vertical tanks ranging from 1,500-gal to over 50,000-gal cryogenic capacity. These tanks are refilled with cryogenic product delivered via a tanker truck. Ammonia and other specialty gases are stored in bulk liquid sources commonly referred to as a tonner or ISO-container. These containers are typically replaced instead of being refilled. For high-volume end-user facilities, on-site gas generation of BAG and hydrogen is common.

Gas purification media

Common purification technologies are selected based on the class of gas, such as: inert, rare, fluorinated, corrosive, toxic, hydride and so on.

Further, the technology choice is refined by the impurity removal required. It is important to avoid using a purifier with a gas or class of gases other than the one for which it was built. Many types of media used for purification are significantly more reactive than media used in front-end gas separation. For example, charcoal may be used in front-end air separation, but activated nickel can only be used for subsequent purification. While charcoal may be safe for air, if a percent-level amount of oxygen is passed through activated nickel, an exothermic reaction may result, generating heat in excess of 1,000°C. Even as inert a material as a molecular sieve will generate significant heat if exposed to saturated moisture.

For most industrial-gas applications, the most common request is for the removal of moisture. This can be achieved using zeolites as purification media, but care must be taken to ensure selection of the proper zeolite for this purpose. As noted, saturated moisture may generate heat, improper pore size may impact efficiency and capacity, and some zeolite media are not compatible with corrosive and other gas classes.

Zeolite use in gas purification is not limited to moisture removal. Zeolites may be used in cryogenic applications to trap a variety of impurities, but the most common use for them is at ambient temperature. Moisture removal is a result of physisorption, as described above. A key difference in the use of zeolites for purification is that activation is completed by flowing gas through the media at an elevated temperature. This method optimizes purification, which can be sized for one year or longer life time.

In applications where removal of oxygen, carbon monoxide, hydrogen, and others is required, metal catalysts are typically used. Metal catalyst may be operated at ambient or elevated temperature. Common metals include nickel, copper and palladium, but a wide range of metal catalysts are available based on the feed gas. Many metals used in purification are not in pure elemental form, but rather, are used as a high-surface-area powder residing on a zeolite support. The quantity of

metal may be as small as 0.5 wt.% for some media. Ambient-temperature metal catalysts operate on the principle of chemical adsorption or chemisorption (Figure 4). In the case of nickel, when contacted by carbon monoxide, nickel carbonyl is formed. Similarly, oxygen within the gas stream forms nickel oxide. These media require the addition of heat and hydrogen for activation. Hydrogen reacts with the catalyst at elevated temperature to reduce the carbon and oxygen bonds, leaving a pure nickel surface.

When removal of methane and nitrogen is required, a rare-earth metal alloy is used. These alloys are commonly Zr-based and are highly reactive with impurities. Operating at temperatures in excess of 300°C, impurity molecules are adsorbed onto the surface and become a permanent part of the alloy, similar to a pill being absorbed in the body. Such media may be used only once, and in contact with impurity levels above 100 ppm, may generate an exothermic reaction stronger than that with nickel and generate heat in excess of 2,000°C.

A wide variety of additional purification technologies, including highly selective membranes, cryogenics, oxides, and so on, also exist, and are available for specialized applications.

Capacity and efficiency

Once the gas source, the purity of the incoming product and the impurities required for removal are understood and the purifier media is selected, the flowrate and pressure need to be determined. Not every medium has the same capacity for each impurity. Metal alloys have a high capacity for removing oxygen, but very limited capacity for nitrogen. Further, capacity is impacted by the quality of the media used. If the goal is to remove moisture from the feed gas stream and a 5A molecular sieve is used, then the removal capacity will be different than using a 13X molecular sieve. Therefore, after a medium is selected, the capacity for each impurity needs to be understood.

Next, the expected lifetime of the purification system needs to be considered. Specifically, the question is how long the purifier needs to last between regeneration or placement. For ambient temperature, zeolite and metal catalyst media, the general rule of thumb is a one-year lifetime, based on the “typical” impurity content within the feed gas stream. As discussed above, the typical impurities can be determined in many gases by simply knowing the method of gas production.

The final consideration surrounds packaging the purifier media. Here, space velocity is important to ensure the gas makes proper contact with the media. Insufficient contact means that flowrate changes, and outlet gas purity will also change. A goal of properly selecting a purifier is to ensure consistent purity with varying flowrates. In many applications, the end users’ processes are as dependent — or more dependent — upon consistency, than upon purity concentrations.

To optimize the final shape of the gas purification system, the aspect ratio, cross-section area, packing density and required pressure loss across the bed need to

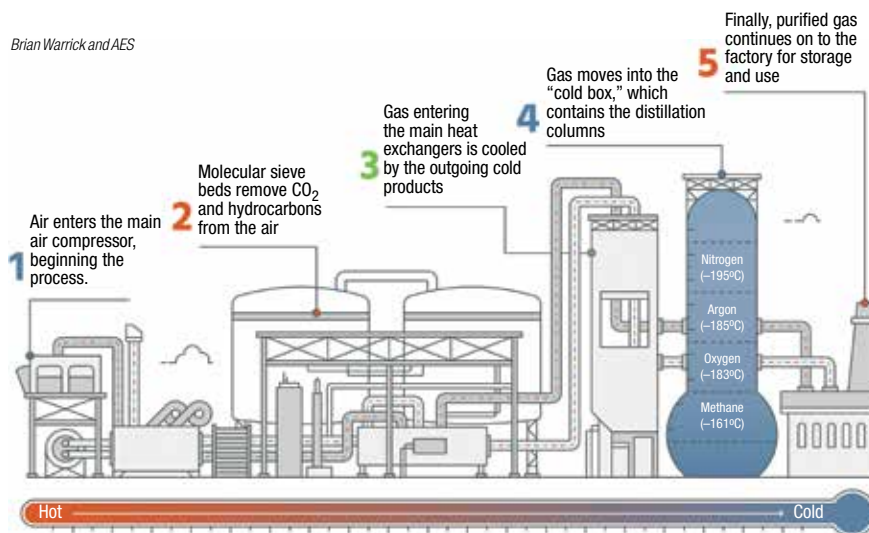


FIGURE 4. Air-separation units, like the one shown here, separate gases according to differing boiling points, using cryogenic distillation

be considered, as well as whether the purifier will fit into the end-user's space constraints. Optimization of the final product is possibly the most critical step in purification. Beyond a laboratory-scale purifier, consistency must be considered to ensure the purifier aligns with existing and potential future equipment design.

The final packaged purifier then needs to be shipped to the end user. Many zeolites and oxides can be sent via standard shipping methods, but many metal catalysts and alloys may require hazardous shipping. The International Air Transport Association (IATA) defines regulations for shipment of all hazardous materials sent via aircraft. Depending upon the hazardous material class and package group, limits on shipping quantities may apply. In these cases, a special permit may be required. Determination of hazardous material and special provision requirements are determined by IATA regulations.

Impurity concentrations

Not all 99.999%-pure gases have the same impurity loading and not all 99.999%-pure gases contain exactly 10 parts per million (ppm) of impurities. When selecting a purifier, a common question is "what is the impurity concentration?" This is the most important aspect of purifier selection and has significant impact on cost and lifetime of the purification system. Nitrogen generated in cryogenic form provides a good ex-

ample. As nitrogen passes through the distillation process, trace amounts of carbon dioxide, moisture, and all hydrocarbons, as well as components with boiling points higher than that of nitrogen, liquify into a waste stream. Nitrogen exits the column containing hydrogen and carbon monoxide, which are not liquified, because of their higher boiling points. Further, if the nitrogen is liquified for cryogenic storage, hydrogen typically flashes from the liquid due to its boiling point. Therefore, nitrogen from a cryogenic source is typically closer to a 99.9999%-pure product. While some specialized distillation processes exist, nitrogen generated from a distillation column is typically the same across grades. What may vary is how the nitrogen is processed following distillation. For higher purity grades, enhanced transport and analytical testing is used to ensure the delivered product is of the highest purity. The gas may have a certificate of conformity. Other gases follow similar behavior, specifically that the impurity content within the gas may be predicted by how the product was generated.

A common element of the separation methods referenced above is the use of an adsorbent or catalyst to remove or separate components. Purification is simply an extension of these gas-generation technologies. With the exception of liquid hydrogen, the purity of each technology is 99.999% or greater. For many applications within the elec-

tronics industry, purity on the order of 99.9999999% is required. Therefore, enhanced technologies are required to further drive purity to these levels. A plot in the online version of this article demonstrates oxygen, moisture and carbon dioxide impurities removed to less than 50 ppt. When discussing the purity of a gas, a common terminology is to refer to the number of nines used to express the purity level. For example, a gas of 99.999% purity is referred to as a "5 nines" (5N) gas and may contain up to 10 ppm of total contaminants. For industrial gas purification, purity of 7 nines (7N; less than 100 ppb of impurities) to 9 nines (9N; less than 1 ppb of impurities) is common.

7N or higher purification technology exists for most industrial gases, but not all impurities can be removed from each gas. An example is oxygen, which contains high-ppm levels of inert gases. Standard purification technologies do not offer a means of removing inert gases from oxygen. Therefore, purified oxygen may be only a 5N gas, even though methane, moisture, hydrogen, carbon monoxide and carbon dioxide are removed to low-ppb levels. ■

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Tailgas Considerations for Biogas Upgrading

Thermal oxidation is used to destroy tailgas from biogas-upgrading facilities. Presented here are guidelines for selecting the proper method



Anoosheh Oskouian and Mike Pawlowski
Ship & Shore Environmental Inc.

IN BRIEF

THERMAL OXIDIZER
SELECTION

DIRECT-FIRED THERMAL
OXIDIZERS

REGENERATIVE THERMAL
OXIDIZERS

With the evolving economics of renewable energy credits comes increased interest in biogas-upgrading facilities. Renewable natural gas (RNG) plants are being designed and built at a remarkable pace. Many scholarly articles have been written to address the pros and cons of each popular method of biogas enhancement. The objective is to process as much of the methane into a high-purity form for injection into the natural gas pipeline, while efficiently removing all undesirable impurities from the raw gas. These impurities include O_2 , H_2O , H_2S , N_2 , CO_2 and other trace amounts of volatile organic compounds (VOCs) that are present in the feed.

A combination of technologies is often used to accomplish this goal, and most of the facilities, at some point, must deal with the issue of disposing or destroying the impurities that are removed from the incoming raw gas. Since the tailgas contains VOCs, thermal oxidation is often employed. This article is a general guideline for selecting the proper method of thermal oxidation that will effectively and efficiently destroy tailgas produced by the typical biogas-upgrading facility.

Thermal oxidizer selection

Thermal oxidation is the controlled combustion of process gases. The process is gov-

FIGURE 1. Direct-fired thermal oxidizers, such as those shown here, can destroy greater than 99.9% of volatile organic compounds in tailgas

erned by time, temperature and turbulence. The overriding parameter is temperature. Typically, for non-halogenated compounds, 1,500°F is required to destroy VOCs when sufficient turbulence is present, and the mixture is retained at that temperature for 0.5 s or more, with the proper volume of oxygen for combustion. Evaluating the type of thermal oxidizer used is critical for optimal plant economics.

The selection process for thermal oxidizers is driven by the conditions of the incoming gas stream: volume and composition of gas to be treated, heat value of the stream (Btu/ft³), and temperature are important factors. Also needing consideration are the regulations for air permitting driven by the local regulatory body. Evaluation of all these factors will provide a solution to the question of which type of oxidizer is right for any given process.

By far, the most effective type of thermal oxidizer is a direct-fired unit (DFTO), which can achieve greater than 99.9% destruction of VOCs (Figure 1). Most often, DFTOs are the least costly type to procure, but depending on the contribution of thermal energy from the incoming stream, they can be the most costly to operate. DFTOs are best for

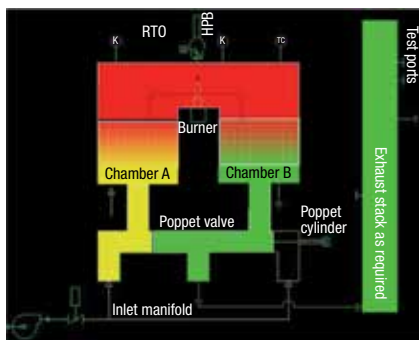


FIGURE 2. In an RTO, process exhaust enters the heat exchanger, where it is pre-heated

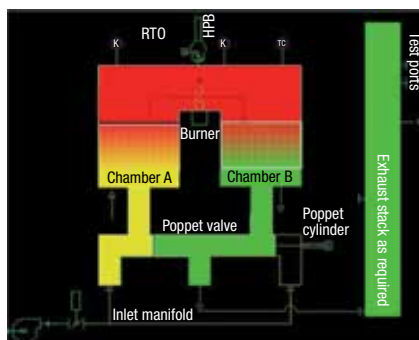


FIGURE 3. The energy value of the exhaust stream may be sufficient to sustain the oxidation process

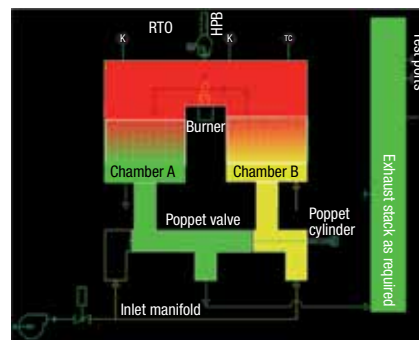


FIGURE 4. Poppet valves close off Chamber A on the inlet stroke

processes where the tailgas has sufficient VOCs to support self-sustaining direct combustion, (typically equivalent to 6 vol.% methane).

DFTOs can be coupled with a variety of heat-recovery options, including heat-recovery steam generators (HRSGs), hot-water or hot-oil systems, and air-to-air heat exchangers. For applications with low volumes of incoming gas or high heating values, it is most often a cost-effective solution to destroy tailgas, as the cost of operation is directly related to the amount of heat required to raise the temperature of the incoming stream, along with required combustion air, to 1,500°F.

A direct-fired unit is the most compact type of thermal oxidizer per cubic foot of incoming process gas. It is typically the least costly to purchase because the volumes required for retention of the gas are minimized by the simple nature of the process. A burner is provided to initially raise

the temperature of the combustion chamber to the proper operating level of 1,500°F. Once at this level, the process gas can be safely introduced to the chamber for destruction.

As internal temperature rises, the start-up burner proportionally reduces the supplemental fuel introduced and the process is managed by controlling the proper amount of dilution air to manage the chamber temperature at a setpoint. When the volume of gas changes, the amount of dilution air is proportionally adjusted to maintain chamber temperature. Should the heat content of the incoming stream fall below the level required for self-sustaining operation, the burner will fire and maintain proper destruction conditions in the chamber.

For applications where heat is required for plant operation, the supplemental fuel burner is configured to provide sufficient output of the system to meet the requirements of the process, while still effectively

destroying the VOCs. The heat of combustion of the incoming waste stream thus becomes the supplemental fuel for the heating requirements of the plant.

Regenerative thermal oxidizers

On the other side of the process spectrum, situations where higher volumes of low-heat-content gas are present call for the application of different oxidizer technology. Regenerative thermal oxidizers (RTOs) are typically employed for situations where the heat content of the incoming stream is not sufficient for self-sustaining direct combustion, and where the use of supplemental fuels needs to be minimized. Understanding the operation of a typical RTO is valuable when considering the best equipment for plant operations. An RTO operation sequence is as follows:

1. Process air enters the RTO and into the ceramic-media heat exchanger Chamber A (inlet stroke;

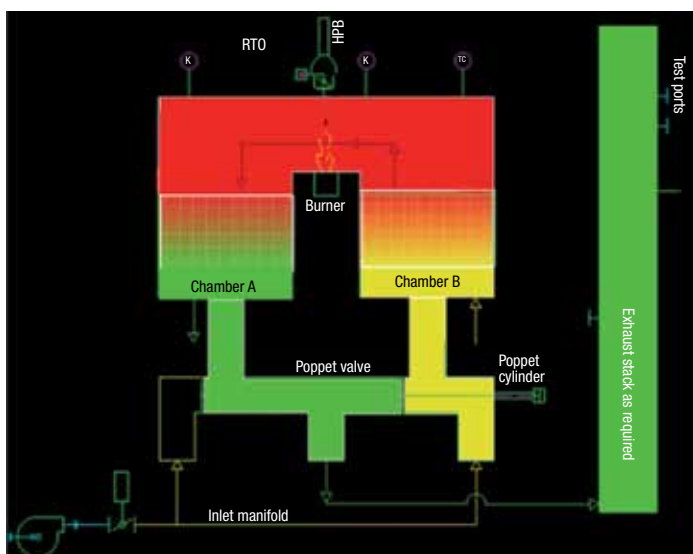


FIGURE 5. Pollutants are oxidized in the combustion chamber and the cleaned gas exits through Chamber A



FIGURE 6. A typical RTO, like the one shown here, can help to optimize the economics of plant operation

Figure 2).

- Process exhaust is preheated in the ceramic media heat exchanger as it migrates toward the combustion chamber
- Air temperature approaches oxidation temperature as it enters the combustion chamber
- Combustion chamber burner provides needed temperature to oxidize the pollutant

2. Heat value (Btu) of the exhaust solvent stream may be sufficient to self-sustain the oxidation process (no burner energy needed; Figure 3)

- Oxidized or clean air exits through the adjoining ceramic media RTO tower Chamber B (exhaust stroke)
- Heat energy is collected from the clean air stream in the ceramic media
- Clean air exits to the RTO exhaust stack and then to the atmosphere

3. After a predetermined setpoint, the RTO directional process air valves cycle in the manifold below (Figure 4)

- Pneumatic or hydraulically actuated poppet valves can be used
- Chamber A is now closed off on the inlet stroke (cool from previous pre-heating).
- Chamber B is now open to the process exhaust inlet stream (hot from newly stored heat)
- Exhaust air is now preheated in Chamber B

4. Process air migrates through the ceramic media heat exchanger into the combustion chamber (Figure 5)

- Pollutants are oxidized in the combustion chamber
- Clean air now exits through Chamber A, where combustion heat is stripped
- Clean air exits to the exhaust stack to atmosphere

With the shifting of the valves comes a small amount of the incoming stream, which does not encounter destruction conditions. The resulting destruction effectiveness is 98–99%. However, the reduction in supplemental fuel is dramatic for low-heat-content streams. This is achieved by the high degree of heat recovery (95–97%) possible with this technology. High amounts of inert

components in the tailgas often suggest selecting RTOs for destruction of VOCs with minimal use of supplemental fuels. After all, the point of a biogas-upgrade facility is to put methane in the pipeline, not consume it in the process. It is understood that small amounts need to be used for startup and for safe, efficient operation of the process.

Like any other form of thermal oxidation, a startup burner is employed

to raise the temperature of the unit to proper destruction conditions. Once at proper temperature, the process gas can be introduced, blended with the correct amount of dilution/combustion air and the RTO cycles through the sequence of operation previously pictured. The burner will provide supplemental fuel to maintain the combustion chamber temperature should the heat content fall below that required for self-sustain-

ing operation. Utilizing a hot-gas bypass can expand the range of possible operating conditions by diverting some of the combusted air directly to atmosphere, rather than sending it through the heat-recovery media.

Utilization of RTOs can assist with optimizing the economics of plant operation (Figure 6). While an RTO unit costs more to purchase per cubic foot of incoming gas than a DFTO, the savings in supplemental

fuel for low-heat content streams normally result in the technology paying for itself rather quickly. Important considerations for the use of an RTO in the process include the following: variability of the incoming stream volumes' heat content; temperature; and the presence of substances that can foul the ceramic heat-transfer media used in the chambers. Siloxanes will produce SiO_2 , which can deposit on the media, reducing its

effectiveness. While silica-resistant ceramic heat-transfer media can be employed to minimize this potential, it is a factor when considering the use of an RTO for tailgas destruction.

Careful monitoring of the incoming stream is required. LEL (lower explosive limit) sensors and proper programming of the temperature controls and air introduced will keep the process in the safe-operating zone. Annual inspections will keep the valves and seats in the proper condition required for effective destruction.

When choosing a vendor for a thermal oxidation process, it is wise to seek out a company with expertise in all forms of oxidizers. A one-size-fits-all mentality will result in a system that either costs too much to purchase, operate or maintain. A complete understanding of not only the normal operating variations, but all of the potential upset conditions, is critical for the long-term, efficient, economical and safe operation of any thermal oxidation system. Vendors should have extensive process knowledge, and the mindset to match technologies to each facility's process conditions. ■

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Controlling Dust through Pelletizing

Tumble-growth agglomeration can reduce dust in solids-handling processes. Here's how it works

**Chris Kozicki, Ron Eichhorn and
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Handling and processing bulk solids appears in nearly every industrial sector, from energy to agriculture. Dust is a ubiquitous and challenging issue when working with bulk solids, because it can create hazardous or unsanitary work environments, transportation problems and financial waste in the form of lost product.

It is not surprising then, that each year, companies go to great expense to control and mitigate dust. One of the most effective ways to manage dust is through pelletizing — a form of tumble-growth agglomeration (particle size enlargement) that produces rounded or spherical granules. Pelletizing can be an invaluable tool in managing dusty bulk solids that opens opportunities in beneficial reuse applications, creates marketable products and mitigates the handling and processing challenges associated with dust.

The term “pelletizing” is often used to refer to various types of agglomeration. This article references the term as a form of tumble-growth agglomeration carried out on a disc pelletizer.

Dust reduction with pelletizing

Pelletizing significantly reduces dust. Apart from collecting dust into small masses of material, the pelletizing process produces a rounded or spherical granular product (Figure 1). Pelletizing is distinguished from pressure agglomeration, which produce granules with jagged edges that can rub together and degrade into fines. With rounded granules, there are no edges to rub together and break down, allowing pellets to remain intact throughout handling



FIGURE 1. Pelletizing solid materials can reduce dust in solids-handling processes by forming rounded granules (left) from the initial powders (right)

and storage.

Dust may be the byproduct of a process or a recovered residue, a material prone to degradation, or simply a material that is inherently dusty in its natural state. A material in the form of dust presents an array of issues that complicate the handling and use of the material.

Pelletizing alleviates these issues, and as a result, has become a popular technique for solving a variety of different material-handling problems. Several dust-related aspects in which pelletizing can realize benefits are summarized here.

Recovering value. When dust is produced as a process byproduct or residue, it is often made up of, or contains, a valuable material. The recovery of the target component is made difficult by the dusty nature of the material. In cases like these, pelletizing is used as an intermediate step in a larger process to allow for easier recovery of the valuable component. An example of this is in the pelletizing of electric-arc furnace (EAF) dust.

EAF dust is a byproduct of steel production and is rich in metals —

particularly iron, lead and zinc. To recover these metals, EAF dust is roasted in a kiln. Roasting is made especially complicated when the material to be processed is in the form of a dust. Pelletizing allows roasting to be carried out efficiently and economically, offering the following advantages:

- Pellets eliminate the risk of entrainment that dust presents (fines becoming swept up into the airflow and exit through the exhaust gas system)
- Pellets can be produced to a desired size to allow for both better heat movement around the pellets in the material bed and increased heat-transfer efficiency through each pellet for improved metal recovery
- Overall process efficiency is increased, because a higher gas velocity can be used when entrainment is not a concern

In addition to dust containing a valuable component, dust generated from product degradation during handling, transportation or processing generally represents a loss in product. This dust can be

FIGURE 2. Aside from reducing dust, pelletizing products can have other advantages, such as simplifying disposal and improving end use



collected and pelletized for re-introduction to the process in order to recover its value and reduce the amount of loss.

Ensuring safe handling. Depending on the material, dust may be hazardous or create an unsafe work environment through risk of explosion, respiratory risk to workers, or even equipment malfunction resulting from fugitive dust buildup.

Pelletizing significantly reduces dust, largely eliminating these risks. Depending on the material, pelletizing may even aid in the effort to comply with regulatory requirements.

Simplifying disposal. Disposal is substantially complicated by a dusty material; dust can escape during transportation or become wind-

blown upon deposit and spread to surrounding areas, causing unintended consequences.

Pelletizing is used in these settings to eliminate dust so that handling and transportation characteristics are improved and the material can be disposed of without the risk of becoming windblown, or contaminating surrounding areas.

Fostering beneficial reuse. Because of their makeup, many dusts can serve as raw materials for beneficial reuse opportunities, but again, are challenging to manage and offer little value in the form of dust. Pelletizing creates an easy-to-handle product and allows for additive inclusion to tailor the material to its intended reuse application.

Synthetic gypsum, for instance, is an incredibly successful case of beneficial reuse.

Made up of calcium sulfate dihydrate, this industrial byproduct generated at coal-fired power plants can be used in place of natural gypsum in many settings. The use of synthetic gypsum over natural gypsum has no adverse effects and even promotes a more sustainable industry. Its reuse is especially popular in the soil amendment industry where pelletizing creates a saleable product that meets all the expectations of the market.

Improving end use. In addition to the benefits listed previously, transforming dust into a granular form generally creates a more marketable product. Both physical and performance characteristics can be controlled through pelletizing, allowing producers to create a premium product that looks good, handles well and performs as desired, in place of a dusty material that may otherwise be difficult to manage, or incur waste management costs (Figure 2).

Materials that are frequently pelletized include the following:

- Crushed gypsum (natural or synthetic; Figure 3)
- Crushed limestone
- NPK fertilizers
- Soil amendments
- Flyash
- Iron, nickel and gold ore
- Alumina
- Glass
- Silica
- Clays and ceramics
- EAF dust
- Soda ash
- Titanium dioxide
- Zinc oxide
- Organic waste

The pelletizing process

Unlike pressure agglomeration techniques that utilize extreme pressure to mold materials into a specific form, pelletizing (not to be confused with pelleting/extrusion), employs a liquid binding agent and motion to form granules. This non-pressure agglomeration technique is subsequently also referred to as tumble-growth or agitation agglomeration.

The pelletizing process can be broken down into three primary seg-



FIGURE 3. Pelletized synthetic gypsum, such as the material shown here, is one example of a frequently pelletized product



FIGURE 4. Pin mixers are horizontal, continuous mixers that combine material fines and liquid binder

ments: preconditioning, pelletizing and drying.

Preconditioning. Preconditioning is a pretreatment step that prepares

material for processing on the disc pelletizer. Depending on the desired specifications of the end product, preconditioning may or may not

be required. The implementation of a preconditioning step serves the purpose of producing a homogeneous mixture of the liquid (binder) and solid feed, while also producing small “seed pellets” in preparation of the disc pelletizer. Employing a preconditioning step sets the stage for a uniform product and more seamless production throughout the pelletizing line.

While dual-shaft paddle mixers (also known as pugmill mixers) are sometimes used, preconditioning is typically carried out in a pin mixer — a horizontal, continuous mixer known for its ability to efficiently combine material fines and liquid binder into a uniformly blended mixture (Figure 4).

Pelletizing. Where a preconditioning step is not used, the disc pelletizer is where production begins. The disc pelletizer is continuously fed with feedstock and binder. As seed pellets (or fines) are fed onto the unit, they are picked up by the rotation of the disc. The binding agent causes



FIGURE 5. As the seed pellets roll against the added fines, they pick up more material layer by layer, until the desired size of the granules is reached

the material to become sticky. Combined with the tumbling action of the disc pelletizer, fines are encouraged to gather into a mass as they roll against each other (essentially forming the seed pellets that would otherwise be produced during pre-conditioning).

The seed pellets roll against the added fines, picking up more and more material on each rotation —

a layering effect similar to rolling a snowball (Figure 5). Once pellets reach the desired size, they are discharged from the pelletizer and carried to a dryer (typically a rotary dryer; Figure 6).

The addition of a dust hood on the pelletizer may be desirable if a pre-conditioning step is not used, as this will prevent the escape of fugitive dust during processing (where pre-

conditioning is used, material entering the disc is pre-wetted, so dust is less of a concern).

Drying. Drying is the final step in the pelletizing process. Drying “cures” the pellets into their final form, solidifying the bond between components, and bringing the material into the specified end-product moisture range. Reaching the desired product moisture range is important, because overdried pellets will be more likely to break down, causing dust and negating the benefits of pelletizing.

Binding agents

Adequately minimizing dust through pelletizing is largely dependent upon the binding agent, or binder. The binder, even if only water, has a significant influence on the integrity of the end product. Dust in the end product is often generated as a result of an inadequate dry crush strength. While other factors do come into play, the crush strength of the end product may be largely a result of the selected binder.

As such, achieving proper crush strength is a matter of finding not only the right binder, but also the right concentration of binder in the product. Determining factors such as type of binder, binder concentration and binder feedrate are best determined through batch and continuous testing.

Alternatives to disc pelletizing

Pelletizing on a disc offers a highly effective solution to dust mitigation. However, in some cases, the refinement and control of particle size offered by the disc pelletizer may be in excess of what is needed.

In cases such as these, or when only small granules are desired, conditioning or micropelletizing may offer a more suitable solution.

Conditioning. Conditioning generally refers to rough agglomeration of fines with a liquid binder in an effort to reduce dust. Reaching specified particle characteristics is typically not a concern here, since the sole intention is dust reduction. Conditioning follows the same principles of agglomeration as pelletizing.

Conditioning is frequently carried out in a paddle mixer (also sometimes called a pugmill mixer), though a pin mixer may also be used. The

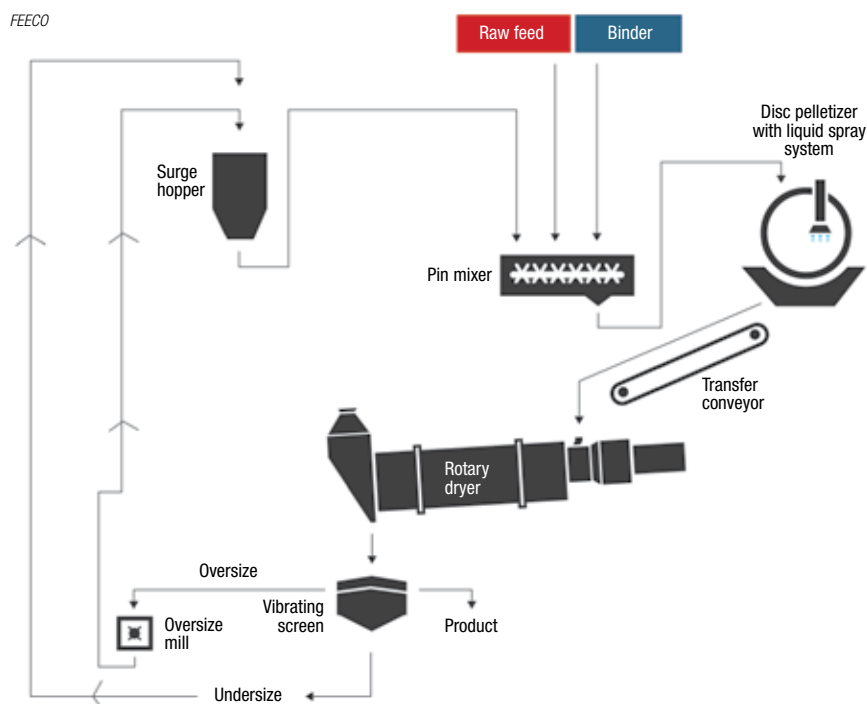


FIGURE 6. A simplified flow diagram of a typical disc pelletizer process (with preconditioning step) is shown here

The binder, even if only water, has a significant influence on the integrity of the end product. Dust in the end product is often generated as a result of an inadequate dry crush strength

paddle mixer is a horizontal continuous mixing device comprised of a U-shaped trough in which two shafts fitted with paddles counter-rotate. The counter-rotation of the shafts produces a motion similar to kneading and folding. Paddle mixers can also be manufactured with a raised and tapered vent (or a simple stub) for dust evacuation.

Depending on the reason for conditioning and subsequent handling requirements, material conditioned in a paddle mixer may or may not be dried. Materials that are regularly conditioned for de-dusting using this approach include the following:

- Cement or lime kiln dust
- Copper and other metallic concentrates
- Foundry dust
- Lead fume
- Flyash
- Iron oxide

Micropelletizing. Micropelletizing is similar to conditioning but occurs in

a pin mixer and generally focuses on creating agglomerates within a specific size range — typically between 18 and 60 mesh (1.0 to 0.25 mm). Particles under 18 mesh are generally smaller than what is typically produced on the disc pelletizer.

Micropelletizing also offers effective dust control, without the need for a full-scale pelletizing line. Since micropelletizing is often used for end-use products, or products that will be further processed, it is typically followed by a drying step.

Materials that are often de-dusted via micropelletizing include the following:

- Carbon black
- Coal dust
- Filter media
- Pigments and dyestuffs
- Specialty powders

Coating for added dust control

When creating a premium product where quality is of the highest con-

cern, anti-dusting agents can also be applied to granules after pelletizing in order to further inhibit potential dust generation. The coating process takes place after drying and can utilize a variety of different types of equipment. The most superior coating is achieved with a coating drum. ■

Edited by Scott Jenkins

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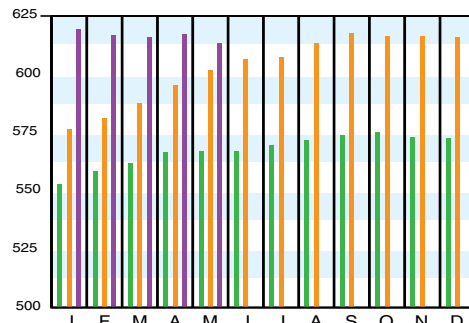
Carrie Carlson is a technical writer who has been with FEECO (same address as above; Email: ccarlson@feeco.com) for nearly a decade. She works closely with engineers and process experts to turn complex ideas into easy-to-understand literature.

Download the CEPCI two weeks sooner at www.chemengonline.com/pci

CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	May '19 Prelim.	Apr. '19 Final	May '18 Final
CEIndex	613.3	617.3	602.9
Equipment	748.6	754.4	735.2
Heat exchangers & tanks	665.5	670.7	653.3
Process machinery	730.5	731.3	718.6
Pipe, valves & fittings	965.4	976.7	958.6
Process instruments	419.1	419.7	422.6
Pumps & compressors	1068.9	1068.4	1022.9
Electrical equipment	557.6	556.1	534.0
Structural supports & misc.	818.0	834.0	799.8
Construction labor	335.6	335.9	331.7
Buildings	597.8	598.3	594.4
Engineering & supervision	316.4	316.9	307.7

Annual Index:
 2011 = 585.7
 2012 = 584.6
 2013 = 567.3
 2014 = 576.1
 2015 = 556.8
 2016 = 541.7
 2017 = 567.5
 2018 = 603.1



Starting in April 2007, several data series for labor and compressors were converted to accommodate series IDs discontinued by the U.S. Bureau of Labor Statistics (BLS). Starting in March 2018, the data series for chemical industry special machinery was replaced because the series was discontinued by BLS (see *Chem. Eng.*, April 2018, p. 76-77.)

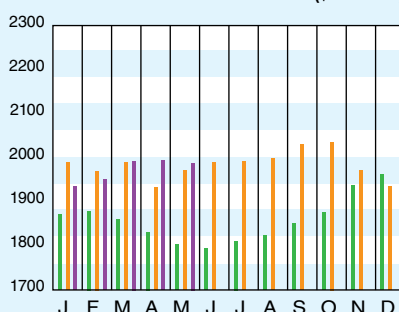
CURRENT BUSINESS INDICATORS

	LATEST	PREVIOUS	YEAR AGO
CPI output index (2012 = 100)	Jun. '19 = 103.1	May '19 = 102.7	Jun. '18 = 103.0
CPI value of output, \$ billions	May '19 = 1,988.5	Apr. '19 = 1,992.9	May '18 = 1,974.5
CPI operating rate, %	Jun. '19 = 77.0	May '19 = 76.8	Jun. '18 = 77.6
Producer prices, industrial chemicals (1982 = 100)	Jun. '19 = 259.3	May '19 = 257.4	Jun. '18 = 272.5
Industrial Production in Manufacturing (2012 = 100)*	Jun. '19 = 105.2	May '19 = 104.8	Jun. '18 = 104.8
Hourly earnings index, chemical & allied products (1992 = 100)	Jun. '19 = 184.6	May '19 = 184.8	Jun. '18 = 183.8
Productivity index, chemicals & allied products (1992 = 100)	Jun. '19 = 96.7	May '19 = 96.2	Jun. '18 = 97.6

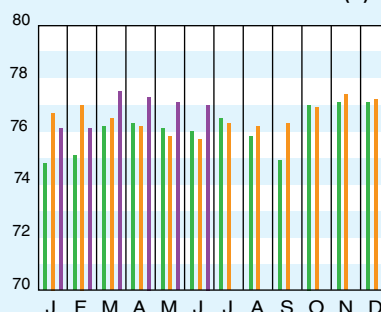
CPI OUTPUT INDEX (2000 = 100)†



CPI OUTPUT VALUE (\$ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.

†For the current month's CPI output index values, the base year was changed from 2000 to 2012

Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the CE Plant Cost Index (CEPCI; top; the most recent available) for May 2019 decreased from the previous month's value. The decline is the third within the last four months. The lower value for the overall CEPCI in May is a result of decreases in all four of the constituent subindices (Equipment, Construction Labor, Buildings and Engineering & Supervision). The overall CEPCI preliminary value for May 2019 stands at 1.7% higher than the corresponding value from a year ago, which is also the smallest year-over-year difference observed since 2016. Meanwhile, the CBI numbers for June 2019 (middle) show a small increase in the CPI Output Index, CPI Operating Rate and Producer Prices.